Wind Turbine Test Wind Matic WM 15S

Friis Pedersen, Troels

Publication date:
1986

Document Version
Publisher's PDF, also known as Version of record

Risø-M-2481

RISØ

Risø-M-2481

Wind Turbine Test
Wind Matic WM 15S

Troels Friis Pedersen

The Test Station
for Windmills

Risø National Laboratory, DK-4000 Roskilde, Denmark
July 1986

RISØ-M-2481

WIND TURBINE TEST
WIND MATIC WM 15S

Troels Friis Pedersen
The Test Station for Windmills, Risø

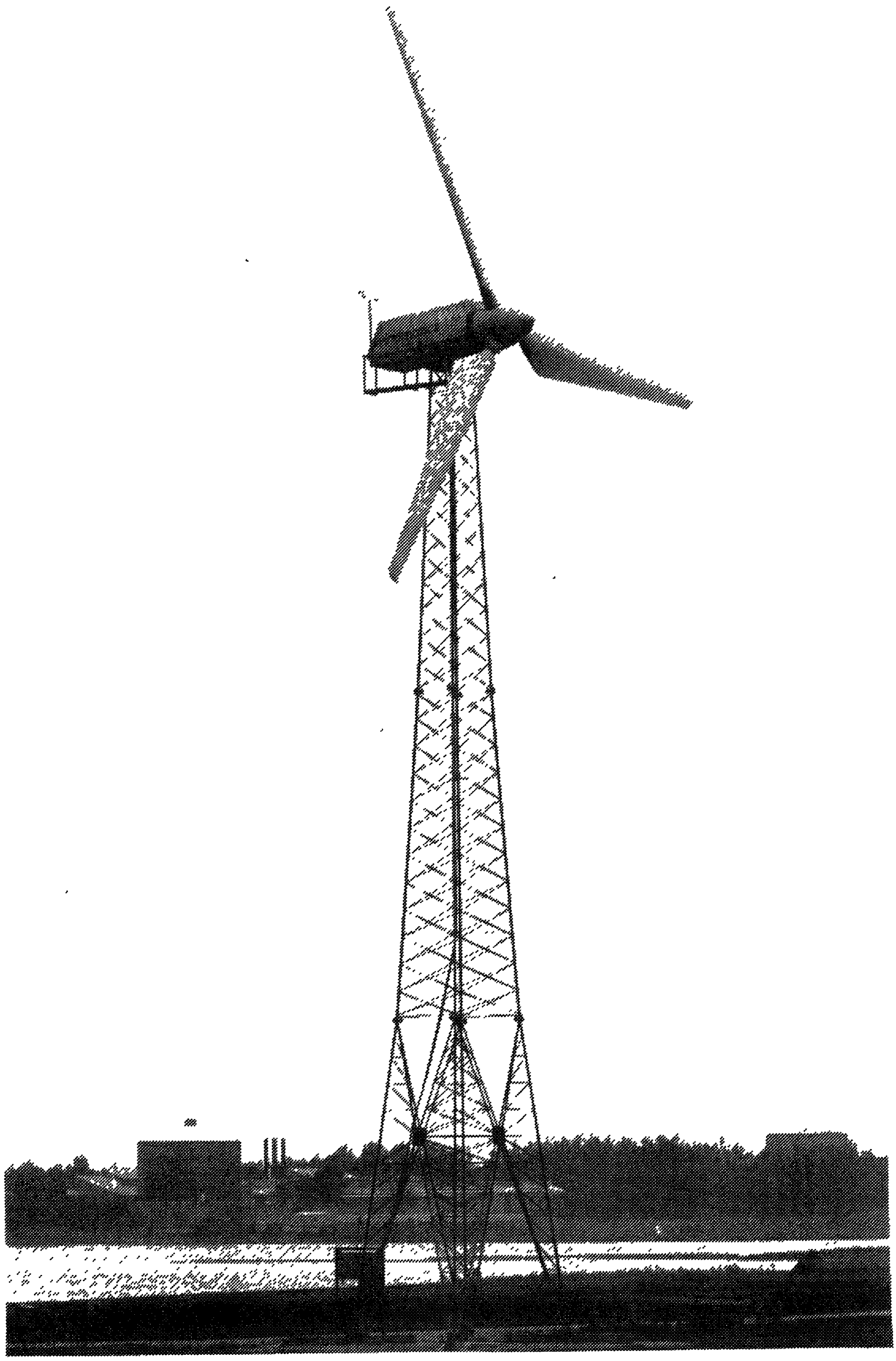
Abstract. The report describes standard measurements performed on a Wind-Matic WM 15S, 55 kW wind turbine. The measurements carried out and reported here comprises the power output, system efficiency, energy production, transmission efficiency, rotor power, rotor efficiency, air-brakes efficiency, dynamical behaviour of the turbine, loads at cut-in and braking, rotor torque at stopped condition, and noise emission.

Risø National Laboratory, DK-4000 Roskilde, Denmark
July 1986

The wind turbine was tested according to a contract with:
Wind Matic A/S, Industrivej Nord 15, Birk, 7400 Herning.

ISBN: 87-550-1263-9
ISSN: 0418-6435

Grafisk Service, Risø 1986



The picture shows the Wind Matic WM15S erected at The Test Station on stand 3.

CONTENT Page

NOMENCLATURE

A	Scale parameter for a Weibull distribution
C	Form parameter for a Weibull distribution
C_e	Overall turbine efficiency; electric power related to wind power
f	The probability for a wind direction in a certain sector.
LA_{eq}	Equivalent A-weighted sound pressure level
L_p	A-weighted sound pressure level
P_e	Electrical power
V	Wind speed
$\bar{V}$	Annual mean wind speed.

1. INTRODUCTION

The Wind-Matic WM 15S wind turbine was erected at the Test Station in March 1984 on stand 3. In September 1984 the large generator and the electronic control system was changed. All measurements that involve the generator and control system were carried out after the changes. The test was completed in February 1985 and the wind turbine was taken down. The measurements performed corresponds to the standard measurement program, which is developed and carried out at the Test Station for Windmills at Risø. This program is described in Ref. 1 and in Ref. 4.

2. THE WIND TURBINE

The wind turbine is in this chapter described to the extent which is of interest concerning the measurements carried out. The rotor is surveyed in details as this is the most important part of the turbine. The principles of the control system are outlined as they are the basis for understanding the safety system and operation of the turbine. Finally, the installation of the sensors on the turbine are sketched. This might be a help for the interpretation of the test results.

2.1 Technical description.

The layout of the nacelle is shown in Fig. 2.1.1. The wind turbine has a three-bladed upwind rotor with fixed cantilevered GRP blades on a welded hub, and the rotor is held by two main bearings with a disc brake in between. The gearbox is mounted on the main shaft behind the bearings and two torque stays are lead to the machine foundation.

The gearbox and the main generator are connected by a stiff clutch. The two induction generators are mounted on a console with a belt drive between them. Yawing of the nacelle is carried out by an electrical motor controlled by a wind vane, mounted on top of the nacelle. The electrical control system is mounted in a stainless steel box on a frame beside the concrete foundation. The tower is of lattice design mounted in three sections. Further specifications are listed in Table 2.1.1.

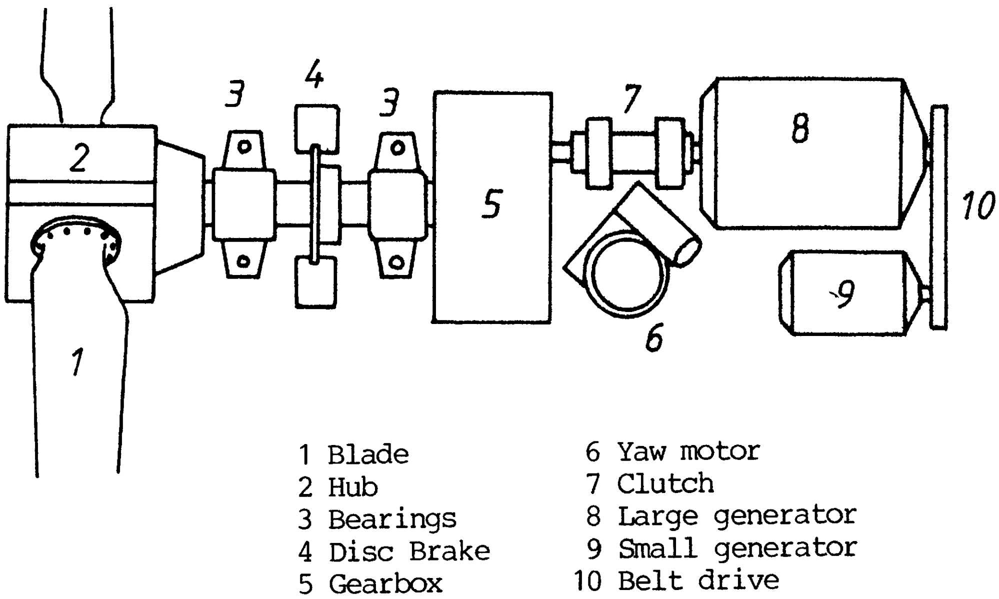


Fig. 2.1.1. Principal lay out of the nacelle.

Table 2.1.1. Technical description of wind Matic WM15S

Rotor

Number of blades:	3
Rotor diameter (measured):	15.56 m
Swept area:	190.2 m^2
Rotor rotational speed (measured):	55 rpm and 39 rpm
Tilt:	5^o
Coning:	0^o
Blade tip angle (measured):	3.2^o, 3.5^o and 3.0^o

Blades.

Type: LM-glasfiber 7.75 m cantilevered GRP blades

Blade weight:	300 kg
Spar materiel:	GRP
Shell materiel:	GRP
Blade length:	7.49 m
Root chord:	1.06 m
Tip chord:	0.47 m
Blade twist:	12.3^{0}
Blade profiles:	NACA 63-200-series
Air brakes:	Individual spoiler type, positioned on suction side at about 45% chord.

Gearbox.

Hansen RHE 31S

Gear ratio:	1:18.315
Gearing ratio between generators:	1:1.43

Generators.

Both generators are induction machines for 50 Hz/380V grid connection.

Primary generator VEM KMER 280 M6.

Nominel power (motor):	55 kW
Synchronous rotational speed:	1000 rpm

Secondary generator VEM KMER 160 L6

Nominel power (motor):	11 kW
Synchronous rotational speed:	1000 rpm

Yaw system.

Electric yaw control with wind vane on nacelle and yaw motor

Mechanical brake.

Disc brake with two calipers, mounted on main shaft between main bearings. Hydraulic activation.

Control system.

Electric control system, based on a microprocessor and a thyristor cut-in, se chapter 2.2
Make: KK Electronics.

Tower.

Welded, galvanised, lattice tower, type	A. Priess A/S
Number of sections:	3
Tower height (measured):	22.34 m

Overall dimensions.

Hub height:	23.04 m
Total height:	30.82 m
Rotor weight (incl. hub):	1180 kg
Nacelle weight (without rotor):	3990 kg
Tower weight:	4827 kg
Total weight:	9997 kg

2.2 Control system and operation.

The control system is based on a microprocessor, which operates via a number of sensors positioned all over the turbine and a high voltage part, which encloses thyristor "soft cut-in" systems for the generators and contactors for different purposes such as yaw drive and brake activation.

The control system has a full automatic operation mode, where the following parameters are supervised, and activation leads to cut-in of the brake. The turbine is not restarted before the failure has been reset.

- grid phase assymetry
- grid voltage failure
- grid frequency failure
- nacelle vibrations
- brake shoe wear
- gear oil level
- brake oil level
- max yaw time
- overspeed
- failure on large generator relay
- failure on small generator relay
- rotor shaft rpm difference from expected
- large generator shaft rpm difference from expected
- thermistor in large generator
- thermistor in yaw drive
- excess temperature in gearbox
- too many cut-in failures on large generator
- failure at cable twist arrangement

The following parameters leads to temporary stops of the turbine with automatic restart.

- air temperature too low
- thyristor temperature too high
- cable twist too high
- excess power production by large generator
- sensor supply voltage failure
- too high wind speed

The automatic operation is carried out the following way. For wind speeds above and rotor rpm below certain levels automatic motor start is activated. Motor start is controlled in power and stopped before the rotational speed of the small generator is reached. If the wind speed is too high, the rotor accelerates to the rotational speed of the large generator. Otherwise it cuts in on the small generator. When the power production is too high on the small generator it cuts out and accelerates to the large generator. When the power production is too low on the large generator, it cuts out and the small generator is cut in to draw the rotor down in rotational speed.

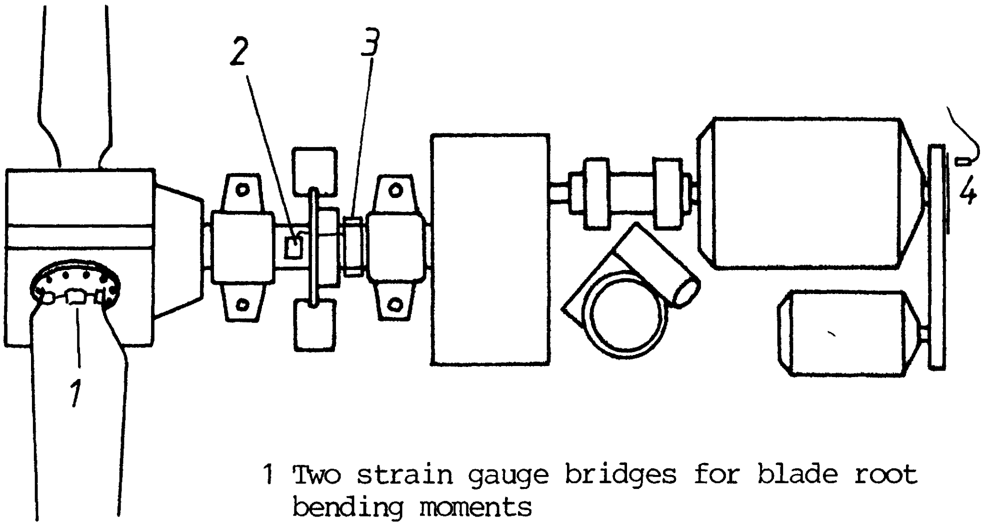
For further information on the operation of the turbine we refer to the operation manual (Ref. 3).

A test of the control system has not been carried out. Only the operation of the brake is tested, see chapter 4.1. During the test period the operation of the turbine has run smoothly, and the control system seems quite reliable.

2.3 Instrumentation.

This chapter deals with the instrumentation of the wind turbine and the sensors used. The overall instrumentation for standard measurements is shown in chapter 3.2.

At the nacelle, the sensors are mounted according to Fig. 2.3.1.



1 Two strain gauge bridges for blade root bending moments

2 Strain gauge bridge for rotor shaft torque

3 One channal FM-transmission equipment

4 Inductive sensor for rotational speed

Fig. 2.3.1. Instrumentation of the nacelle.

One blade was instrumented with two full bridge strain gauge bridges with 360 ohm strain gauges for measurement of flapwise and edgewise bending moments at the root. An 8 channel PCM-transmission equipment with dry batteries was used for bridge supply and data transmission directly to the ground. Data were transmitted as PCM signals to the computer room where the signal was demultiplexed and converted to analog signals.

On the main shaft between the front bearing and the brake disc was mounted a full bridge strain gauge bridge also with 360 ohm strain gauges for measurement of shaft torque. A one channel FM-transmission equipment was mounted close to the strain gauge bridge. This system supplied power to the strain gauge bridge and the data transmission from batteries, but here two coils were mounted around the shaft for the data transmission from the rotating shaft to the nacelle. At the nacelle the signal was converted to an analog signal.

For measurement of rotational speed of the rotor a disc with 9 holes was mounted behind the large generator with an inductive sensor to count the hole frequency.

Close to the sensor a frequency to analog converter was mounted for further data transmission.

Measurement of electric power was carried out with three current transformers, one on each phase, and a power converter that converts the signal to a voltage signal.

The current is measured with a separate current converter but only on one phase. In this connection uneven loads on the three phases is not taken into account.

Wind speed is measured with a cup anemometer with three cups. The rotor is giving 12 photo electric pulses per rotation and this pulse signal is in another box converted to a voltage signal. The anemometer has been calibrated in a wind tunnel at the Technical University of Denmark, but the calibration was later changed due to systematic differencies between this wind tunnel and a 1.8x2.6 m tunnel at Danish Maritime Institute.

The wind direction is measured with a wind vane with a cos/sin resolver. This resolver transmits two voltage signals proportional to the sine and the cosine of the wind direction to the computer room.

Temperature and barometric pressure are measured with two sensors with high accuracy, and they are mounted stationary at the meteorological tower and the computer room accordingly.

3. THE TEST STATION

The conditions for a wind turbine test is a very important basis for the results of the measurements. In the following the conditions for The Test Station are described in chapters comprising the climatological test site, data aquicition and analysis and the load conditions for the turbine.

3.1 The test site.

The Test Station for Windmills is situated at Risø National Laboratory, 5 km north of Roskilde, and 30 km west of Copenhagen. The test stands are positioned on a rather flat area close to Roskilde Fjord (see Fig. 3.1.1). The prevailing winds are westerly coming from the fjord, and most of the measurements are carried out with winds coming from this direction

The meteorological conditions at the test site is measured continuously on a central meteorological tower.

The wind speed is measured at 3, 10, 20 and 33 m's height, and for the period May 1982 to January 1986 the statistical wind distribution has been calculated.

For the four heights the Weibull parameters for the wind speed distributions are shown in Table 3.1.1. Generally the measured distributions fit very well to the weibull distributions.

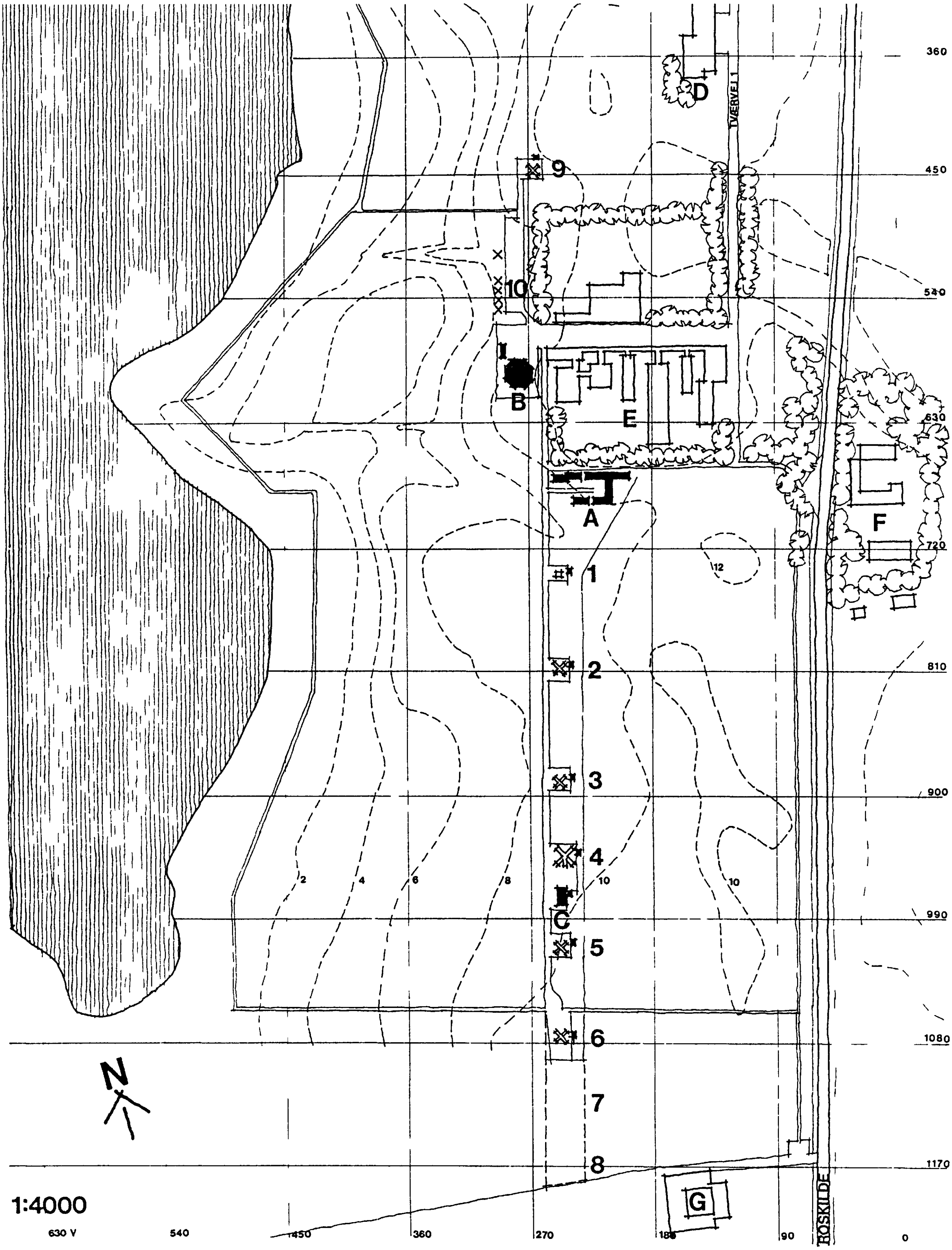


Fig. 3.1.1. Topology at the site.

33 m

	A m/s	C	f %	V m/s
N	4.9	1.77	6.0	4.3
NE	4.1	2.04	5.0	3.6
E	6.4	2.10	10.9	5.6
SE	7.1	2.41	17.0	6.3
S	5.5	2.21	9.7	4.8
SV	6.2	2.34	18.2	5.5
V	7.7	2.12	20.6	6.9
NV	6.5	1.68	12.6	5.8
Total	6.5	2.00	100.0	5.7

20 m

	A m/s	C	f %	V m/s
N	4.2	1.75	5.9	3.8
NE	3.4	2.00	4.9	3.0
E	5.7	1.98	10.8	5.0
SE	6.6	2.38	16.9	5.9
S	4.8	2.17	9.6	4.2
SV	5.7	2.26	18.3	5.0
V	7.4	2.13	20.9	6.5
NV	6.3	1.76	12.7	5.6
Total	6.0	1.93	100.0	5.3

10 m

	A m/s	C	f %	V m/s
N	3.8	1.73	5.8	3.4
NE	2.9	1.86	4.8	2.6
E	4.8	1.87	11.9	4.3
SE	5.8	2.25	16.4	5.1
S	4.3	2.03	9.9	3.8
SV	5.4	2.21	18.8	4.7
V	7.1	2.17	19.8	6.3
NV	5.9	1.77	12.5	5.3
Total	5.5	1.87	100.0	4.8

3 m

	A m/s	C	f %	V m/s
N	3.2	1.71	5.6	2.9
NE	2.5	1.75	4.6	2.2
E	3.8	1.66	13.4	3.4
SE	4.7	1.97	16.6	4.1
S	3.5	1.88	9.9	3.1
SV	4.5	2.14	17.3	4.0
V	5.7	2.10	20.2	5.1
NV	4.8	1.80	12.3	4.2
Total	4.4	1.79	100.0	4.0

Table 3.1.1. Weibull parameters for wind speed distributions at the test site.

The annual mean wind speed is 5.3 m/s at 20 m height and 5.7 m/s at 33 m. The prevailing wind directions are shown to be west and southwest, which also are the wind directions used for the measurements on the wind turbines. Stationary masts for wind speed measurements are therefore placed perpendicular to the row of test stands, which has an orientation from 15° north to 195° south. Fig. 3.1.2 shows a sketch of the test stands.

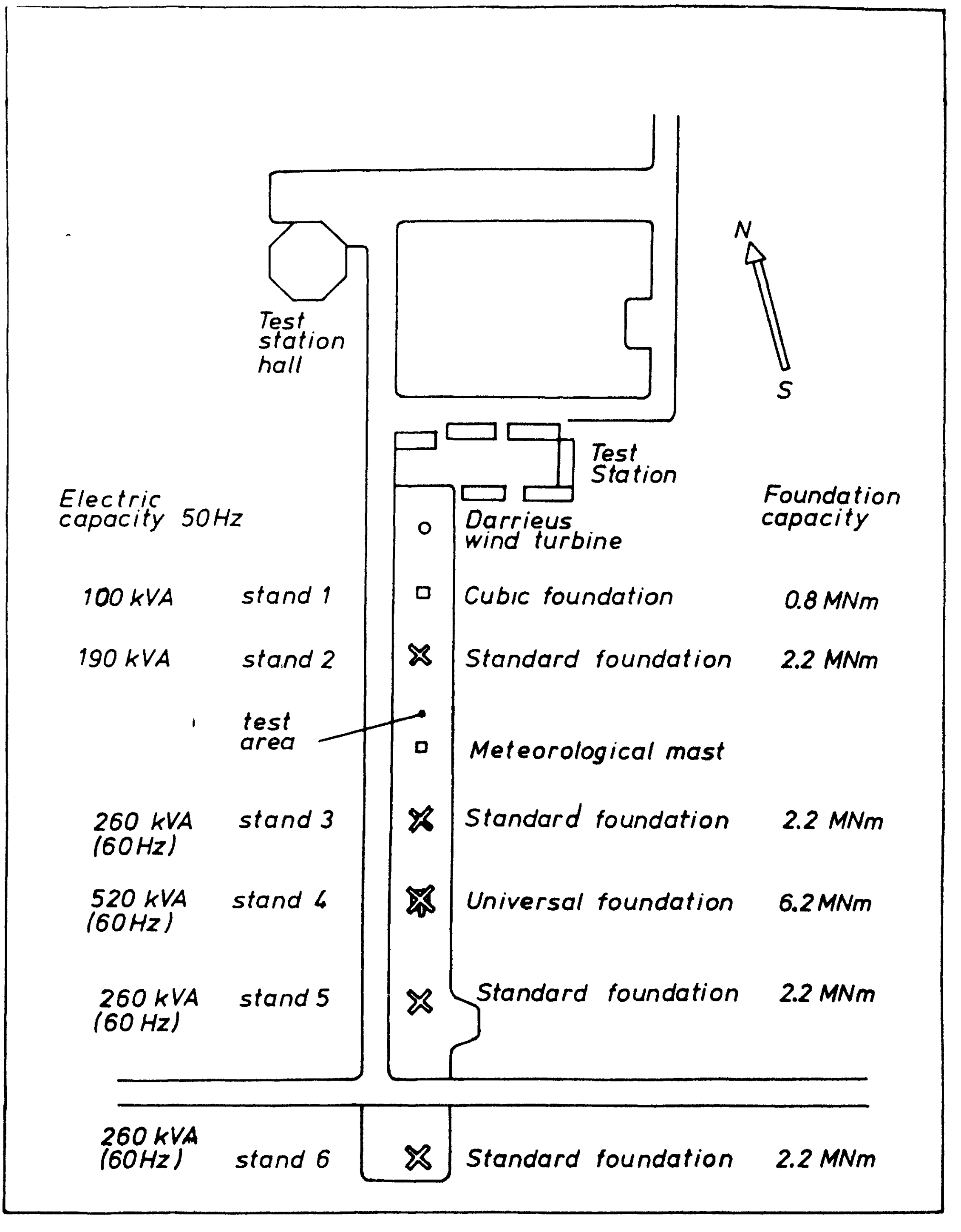


Fig. 3.1.2. The test stands for wind turbine testing.

3.2 Data aquicition and analysis.

The measurement system at The Test station has multi channel DC-cables from each test stand to the computer room for transferring data. The sensors are supplied with power from power supplies at each test stand, and the signals are transferred with a voltage range from - 5V to + 5V. Fig. 3.2.1 shows the cabling used for the standard measurements.

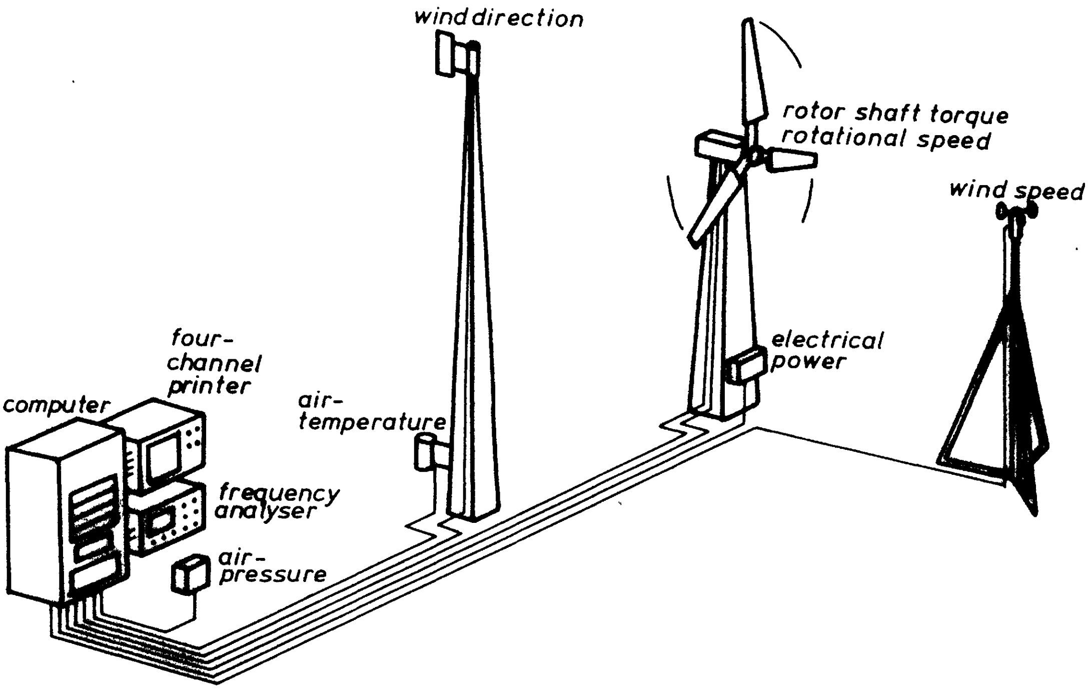


Fig. 3.2.1. Transmission lines used for the standard measurements.

At the computer room all channels pass through a filter that protects the computer equipment from lightning. Afterwards they pass through a low pass filter module with a cut off frequency of 0.4 Hz or 20 Hz. Alternatively the signal can pass directly through.

After the filter module the signals can go directly to a strip chart recorder for time trance recording, to a spectrum analyzer for frequency analyzes or to the computer for data aquicition. Before the computer the analog signals are converted to digital representation with a 12 bit resolution for the ±5V voltage range.

For measurements of power curve, transmission efficiency and air brakes the 0.4 Hz filter and a sample frequency of 1 Hz is used. The electric power and rotor torque is corrected to a standard air density of 1.225 kg/m^2, corresponding to an air temperature of 15° C and barometric pressure of 1013.3 mbar. This is in accordance with the IEA-recommendation (Ref. 2).

The sampled data are averaged over 30 seconds and 10 minutes. Data analysis is now performed using the Method of Bins with a bin width of 0.5 m/s. The centers of the bins are at each half and full m/s. For each bin the wind speed, electric power, rotor rotational speed and rotor torque is averaged and for electric power and rotor torque the standard deviation is calculated.

For power curve measurements only at 90° sector from 240° at southwest to 330° at north west is included in the data analysis and the data shall contain at least 200 hours of 10 minutes average data, and only bins with more than 3 averages are included. The power curve is extended by 30-sec averages at higher wind speeds but only for at least 3 averages. It is pointed out, that data from the 30 sec averages are based on far fewer operating hours, and the accuracy of these data is correspondingly lower.

Correction for wind shear is not performed as the wind speed sensor is positioned at hub height at a distance of minimum two rotor diameters from the wind turbine and maximum four rotor diameters from it.

For measurements on air brakes 30-sec average data are used but with a 120° sector.

3.3 The load for the turbine.

The turbine was tested on a 50 Hz, 3 x 380 V grid, which was connected to a 350 kW transformer raising the voltage level to 10 kV. At the time of the testing all turbines in the test row, see Fig. 3.1.3, were connected to the same transformer.

4. SAFETY TESTS

A windmill has one or more safety systems with the purpose of keeping the turbine from overloading in emergency situations. Testing of these systems is therefore important to insure safe operation. In this chapter the measurements are reported on the mechanical brake and the air brakes.

4.1 Test of mechanical brake.

The mechanical brake was tested in two ways. The loads at normal stop, where the "STOP" button is pressed, were recorded and afterwards the same was measured by disconnecting the main switch for the grid.

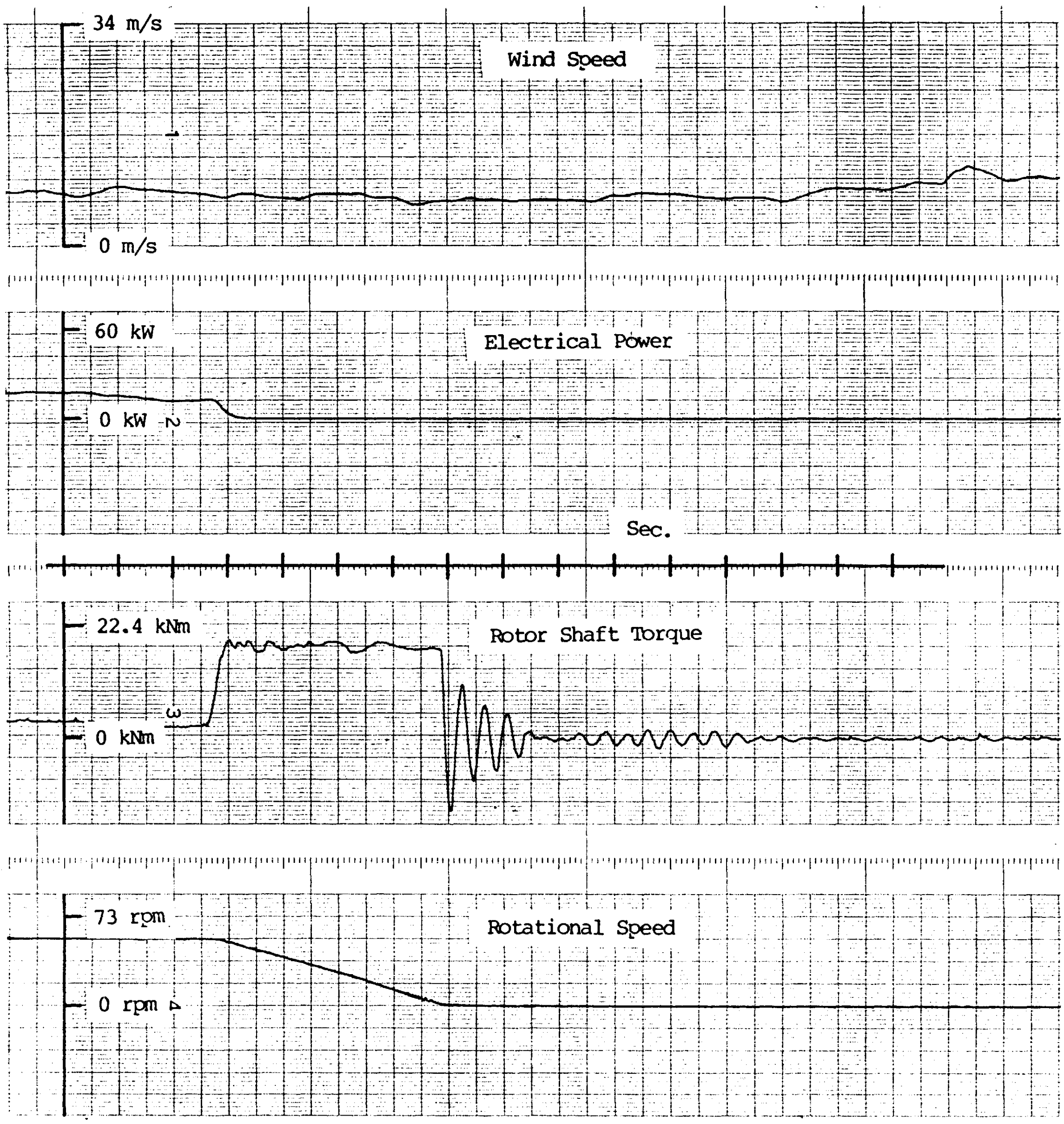
Fig. 4.1.1 shows the result of a normal stopping procedure. The power was approximately 12 kW on the large generator when the "STOP" button was activated. It is seen, that the brake torque increases to full torque in about 0.3 sec, and gradually takes over the power from the generator. No transients are seen at the cut-in of the brake or at cut-out of the generator. The brake torque is kept rather constant at 19.0 kNm throughout the stop sequence. When stopped, the rotor oscillates at a frequency of 2.4 Hz but the damping in the system brings it to stop in about 4 cycles. The stop procedure was repeated four times and the result was the same each time.

The braking sequence by disconnecting the main switch for the grid is shown in Fig. 4.1.2. The power was at a maximum of about 60 kW when the large generator was cut-out. A slight acceleration of the rotor is seen while the brake torque builds up. A drive rain eigenfrequency of 4.6 Hz is seen during this phase. Full brake torque peak of 22 kNm is seen while the drive train oscillations are damped out, and afterwards the brake torque is constantly 19.0 kNm.

The brake torque of 19.0 kNm is 1.99 times that of the torque at 55 kW electric power and 55 rpm.

Wind Matic WM15S

Activation of Mechanical Brake



Brake is activated by pushing the 'STOP'-botton
on the control system.
Measurement period: 23-Jan-85

TURBINE DATA

Rotor diameter: 15.56 m
Swept area: 190.2 m**2

Rotational speed: 39 rpm and 55 rpm
Tip angle: 3.0, 3.2 and 3.5 deg

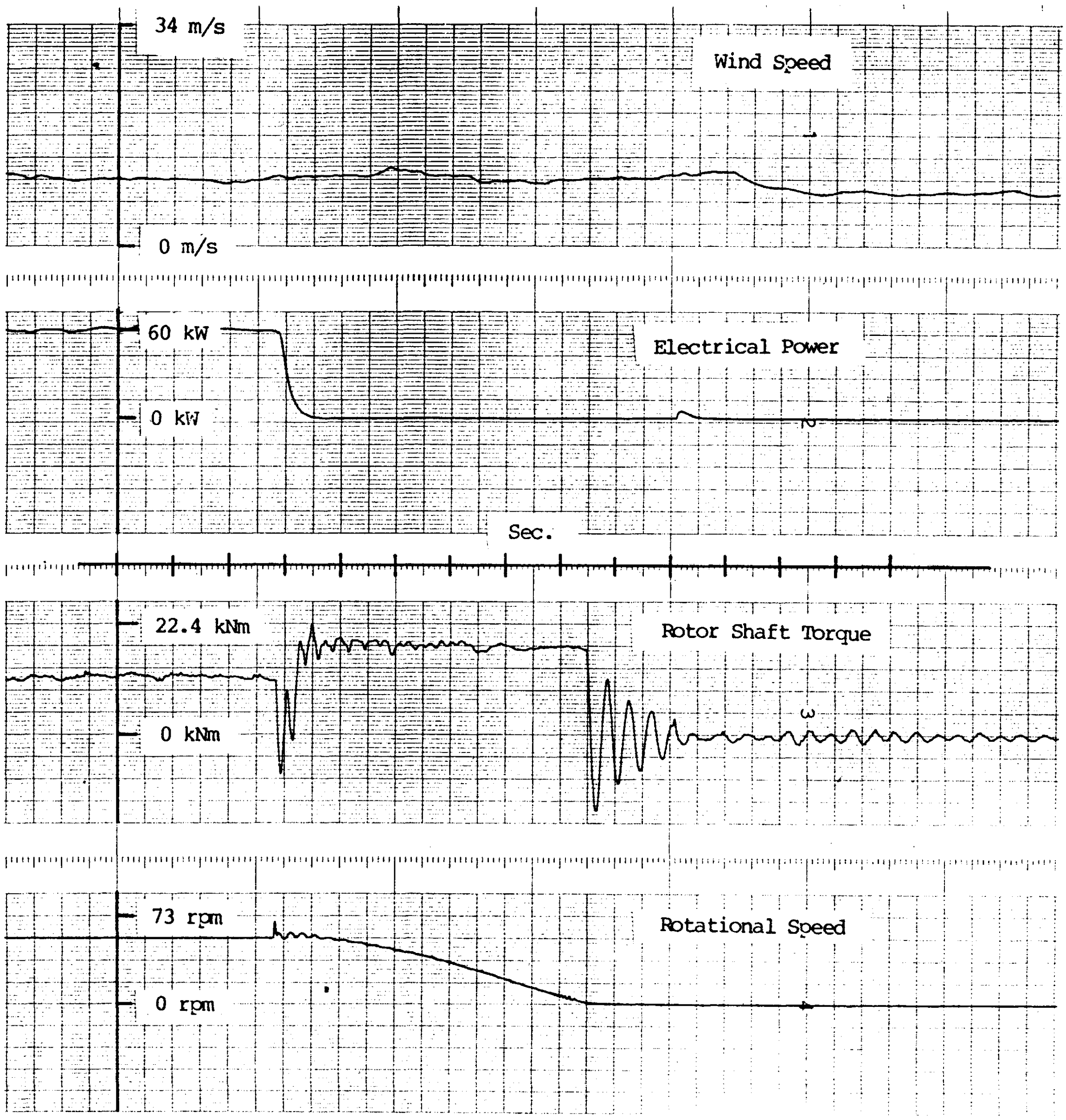
RISØ

THE TEST STATION FOR WINDMILLS
Drawn: 12-DEC-85 Report: RISO-M-2481

Fig. 4.1.1 Mechanical brake ("STOP" button)

Wind Matic WM15S

Activation of Mechanical Brake



Brake is activated by disconnecting the main switch for the grid.
Measurement period: 23-Jan-85

TURBINE DATA

Rotor diameter: 15.56 m	Rotational speed: 39 rpm and 55 rpm
Swept area: 190.2 m**2	Tip angle: 3.0, 3.2 and 3.5 deg

RISØ THE TEST STATION FOR WINDMILLS
Drawn: 12-DEC-85   Report: RISO-M-2481

Fig. 4.1.2 Mechanical brake. (Main switch).

4.2 Test of air brakes.

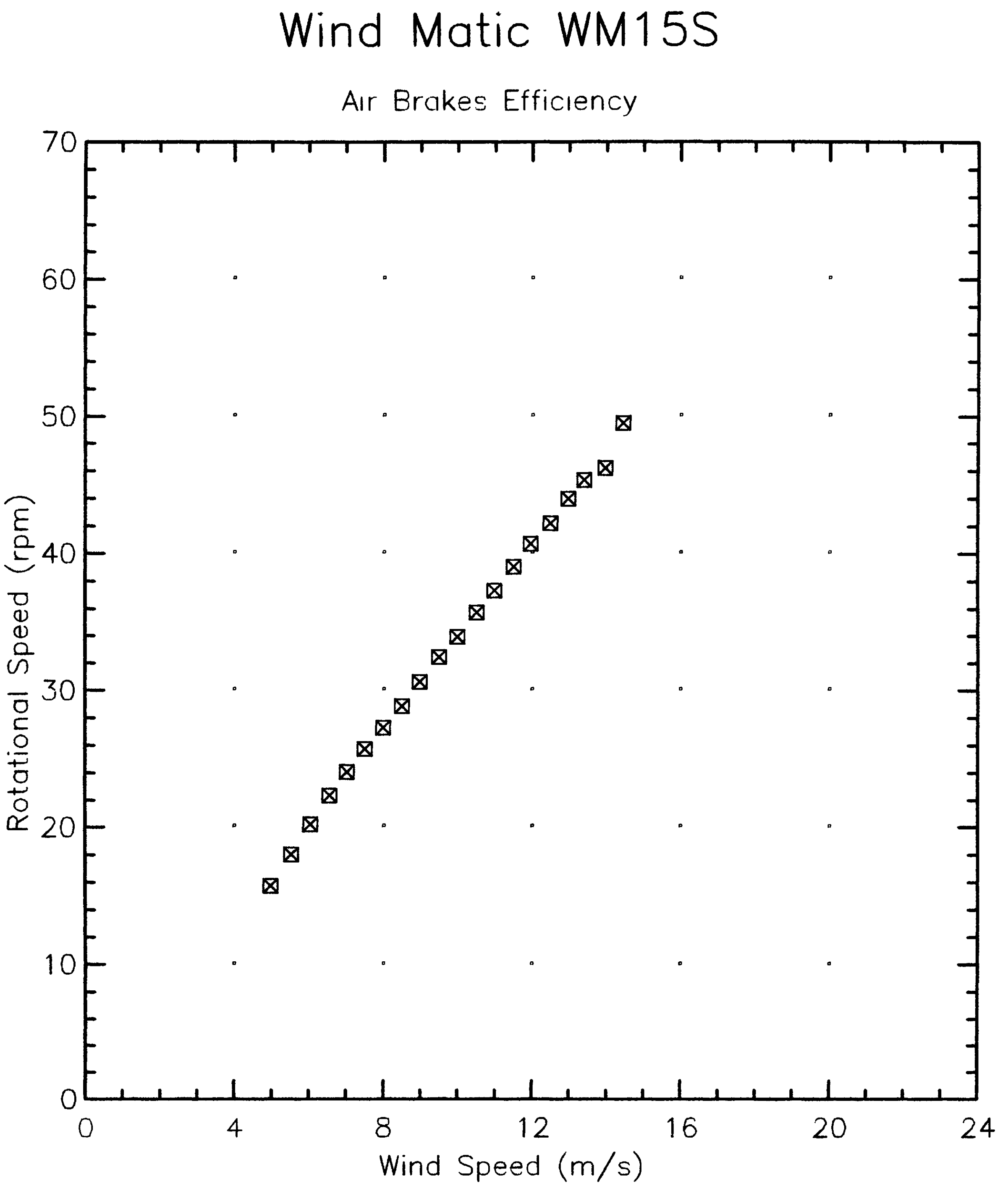
The air brakes were tested in June 1984 by letting the rotor run loose. The air density was 1.230 kg/m3 and in a 12 m/s wind the rotor accelerated above normal rotational speed. Two spoilers were activated almost simultaneously and the third was activated a few rotations later. When activated, the spoilers stayed in the fully activated position throughout the measurement period.

The efficiency of the air brakes was measured during an 18 hour period where 30-sec average data was used with the method of bins. The result is shown in Fig. 4.2.1 and tabulated in Table 4.2.1.

The result shows a rather linear relation between wind speed and rotational speed. An extrapolation of the curve shows, that the normal rotational speed of 55 rpm is reached at a wind speed of 16 m/s. At wind speeds at 20, 30 and 40 m/s the rotational speed must be expected to be 67, 101 and 134 rpm presuming that the linearity holds.

These rotational speeds are very high and therefore special precautions must be taken at sites with high extreme wind speeds.

It is recommended that an effort is put to develop more efficient air brakes.



Data origin: Measurement
Measurement period 26-Jun-84
Total measurement time 18 Hours

TURBINE DATA

Rotor diameter 15.56 m
Swept area 190.2 m**2

Rotational speed 39 rpm and 55 rpm
Tip angle 3.0 3.2 and 3.5 deg

RISØ THE TEST STATION FOR WINDMILLS
Drawn: 04-DEC-85 Report: RISO-M-2481

Fig. 4.2.1. Efficiency of air brakes on WM15S

Table 4.2.1. Efficiency of air brakes.

Wind Matic WM15S RISO-M-2481

ROTOR DIAMETER (M): 15.56 m
SWEPT AREA (M**2): 190.2 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 3.0, 3.2 and 3.5 deg
MEASUREMENT PERIOD: 26-Jun-84
MEASUREMENT TIME: 18 Hours

MEASURED DATA CURVE: Air Brakes Efficiency

---

3 Spoilers Active

X: Wind Speed (m/s)
Y: Rotational Speed (rpm)

	X	Y
1	4.99	15.710
2	5.53	18.010
3	6.05	20.190
4	6.56	22.300
5	7.02	24.050
6	7.50	25.710
7	8.01	27.230
8	8.50	28.860
9	8.99	30.630
10	9.50	32.430
11	10.00	33.920
12	10.50	35.690
13	10.98	37.280
14	11.50	39.030
15	11.97	40.700
16	12.49	42.170
17	12.98	43.960
18	13.40	45.330
19	13.97	46.200
20	14.45	49.450

5. PERFORMANCE MEASUREMENTS

The performance of the wind turbine is an important measurement because the economy is to a large extent based on the ability of the turbine to produce power.

Turbine efficiency, transmission efficiency, rotor power and rotor efficiency are important in that they indicate how power is generated and lost in the transmission to useful power.

5.1 Power Curve Measurements.

The power curve was measured in a period from 07.12.1984 to 03.02.1985. In the period 16 runs were carried out but only 4 runs contained wind from the right westerly wind sector. These four runs are tabulated below.

Table 5.1.1 Measurement periods for power curve.

		Average for the measurement period			
date	hours	wind speed	air pressure	air temp.	turb. intensity
07/12-84	48	7.44 m/s	1018 mBar	6 deg.	0.148
10/12-84	36	6.12 m/s	1020 mBar	4 deg.	0.143
30/01-85	6	7.95 m/s	1016 mBar	1 deg.	0.091
01/02-85	64	8.7 m/s	1013 mBar	-1 deg.	0.116

The data from these runs are corrected to a standard air density of 1.225 kg/m^3 and averaged. The power curve is shown in Fig. 5.1.1. with 30-sec average data as a dashed line.
In Table 5.1.2 the power and the turbine efficiency curves are tabulated. 30-sec average data are shown in parenthesis. The wind turbine efficiency is shown in Fig. 5.1.2.

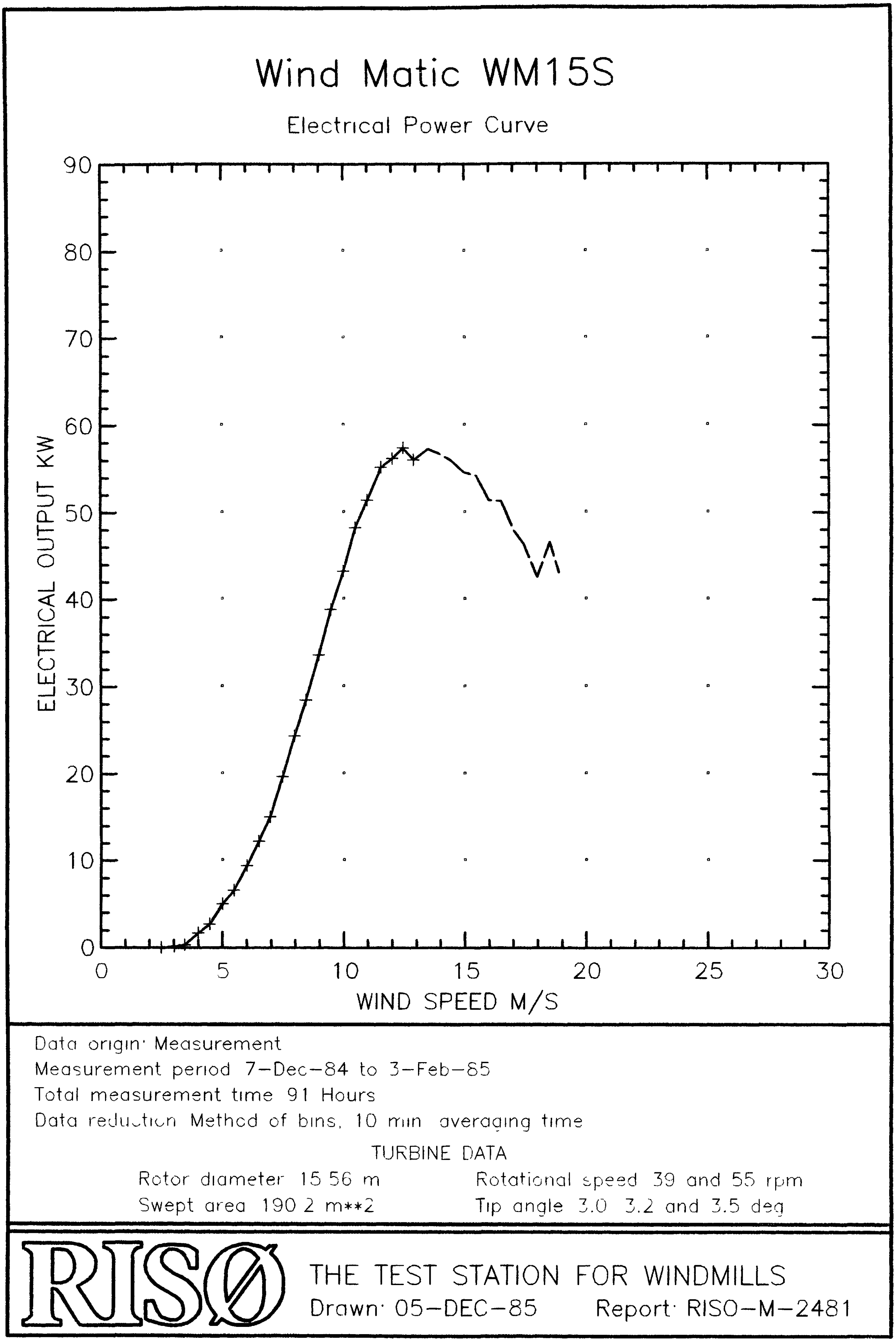


Fig. 5.1.1. Measured power curve for Wind-Matic WM15S

Table 5.1.2. Measured power curve for Wind-Matic WM15S

WIND TURBINE: Wind Matic WM15S REPORT: RISO-M-2481

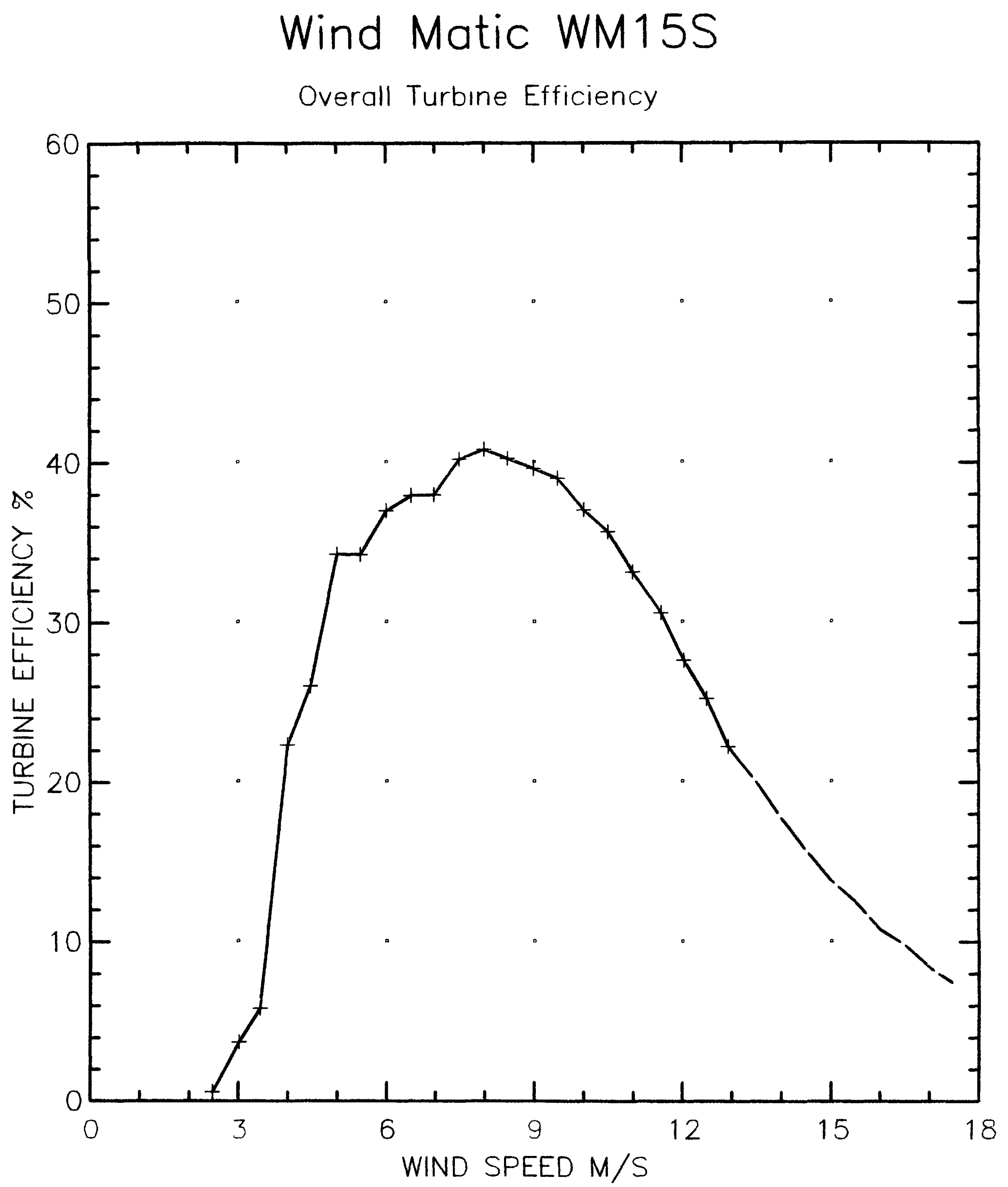
ROTOR DIAMETER: 15.56 m
SWEPT AREA: 190.2 m**2
ROTOR SPEED: 39 and 55 rpm
TIP ANGLE: 3.0, 3.2 and 3.5 deg
MEASUREMENT PERIOD: 7-Dec-84 to 3-Feb-85
MEASUREMENT TIME: 91 Hours

MEASURED POWER CURVE

MEASUREMENTS ARE BASED ON 10-MIN. AVERAGES
DATA IN PARENTHESIS ARE BASED ON 30-SEK AVERAGES

	WIND SPEED m/s	WIND SPEED mph	EL. POWER kW	AVERAGES NO.	OVERALL EFFICIENCY
1	2.48	5.55	0.010	12	0.006
2	3.02	6.76	0.120	13	0.037
3	3.45	7.72	0.280	7	0.059
4	4.01	8.97	1.680	14	0.224
5	4.47	10.00	2.710	9	0.260
6	5.01	11.21	5.020	16	0.343
7	5.49	12.28	6.600	34	0.342
8	6.02	13.47	9.400	32	0.370
9	6.52	14.59	12.260	46	0.380
10	6.98	15.62	15.060	56	0.380
11	7.49	16.76	19.700	46	0.402
12	8.00	17.90	24.370	40	0.409
13	8.47	18.95	28.510	33	0.403
14	9.00	20.14	33.680	18	0.397
15	9.49	21.23	38.860	24	0.390
16	10.01	22.40	43.280	38	0.370
17	10.51	23.52	48.260	36	0.357
18	11.00	24.61	51.390	24	0.331
19	11.57	25.89	55.210	17	0.306
20	12.04	26.94	56.220	13	0.276
21	12.50	27.97	57.440	10	0.252
22	12.93	28.93	56.030	5	0.222
23	(13.50)	(30.21)	(57.280)	(206)	(0.200)
24	(13.99)	(31.30)	(56.760)	(152)	(0.178)
25	(14.46)	(32.35)	(55.980)	(76)	(0.159)
26	(15.00)	(33.56)	(54.590)	(47)	(0.139)
27	(15.50)	(34.68)	(54.250)	(36)	(0.125)
28	(16.01)	(35.82)	(51.390)	(21)	(0.107)
29	(16.52)	(36.96)	(51.280)	(23)	(0.098)
30	(17.03)	(38.10)	(47.950)	(14)	(0.083)
31	(17.46)	(39.07)	(46.270)	(10)	(0.075)
32	(17.99)	(40.25)	(42.610)	(6)	(0.063)
33	(18.52)	(41.44)	(46.600)	(7)	(0.063)
34	(18.89)	(42.26)	(43.100)	(4)	(0.055)

STOP WIND SPEED (M/S): 25.0



Data origin: Measurement
Measurement period 7-Dec-84 to 3-Feb-85
Total measurement time 91 Hours
Data reduction: Method of bins, 10 min. averaging time

TURBINE DATA

Rotor diameter 15.56 m	Rotational speed 39 and 55 rpm
Swept area 190.2 m**2	Tip angle 3.0, 3.2 and 3.5 deg

RISØ THE TEST STATION FOR WINDMILLS
Drawn: 05-DEC-85 Report: RISO-M-2481

Fig. 5.1.2. Wind turbine efficiency for Wind-Matic WM15S

The wind turbine starts production at 3 m/s and at 8 m/s it reaches the maximum efficiency of 40.9% at 24.4 kW. Nominal power is reached at 11.5 m/s and maximum power (57.4 kW) at 12.5 m/s. The stall-regulation decreases the power output to about 43 kW at a wind speed of about 18 m/s. Highest 30-sec average wind speed was measured at 18.9 m/s where the power output was 43.1 kW. The stop wind speed of 25 m/s was not reached.

5.2. Annual Energy production.

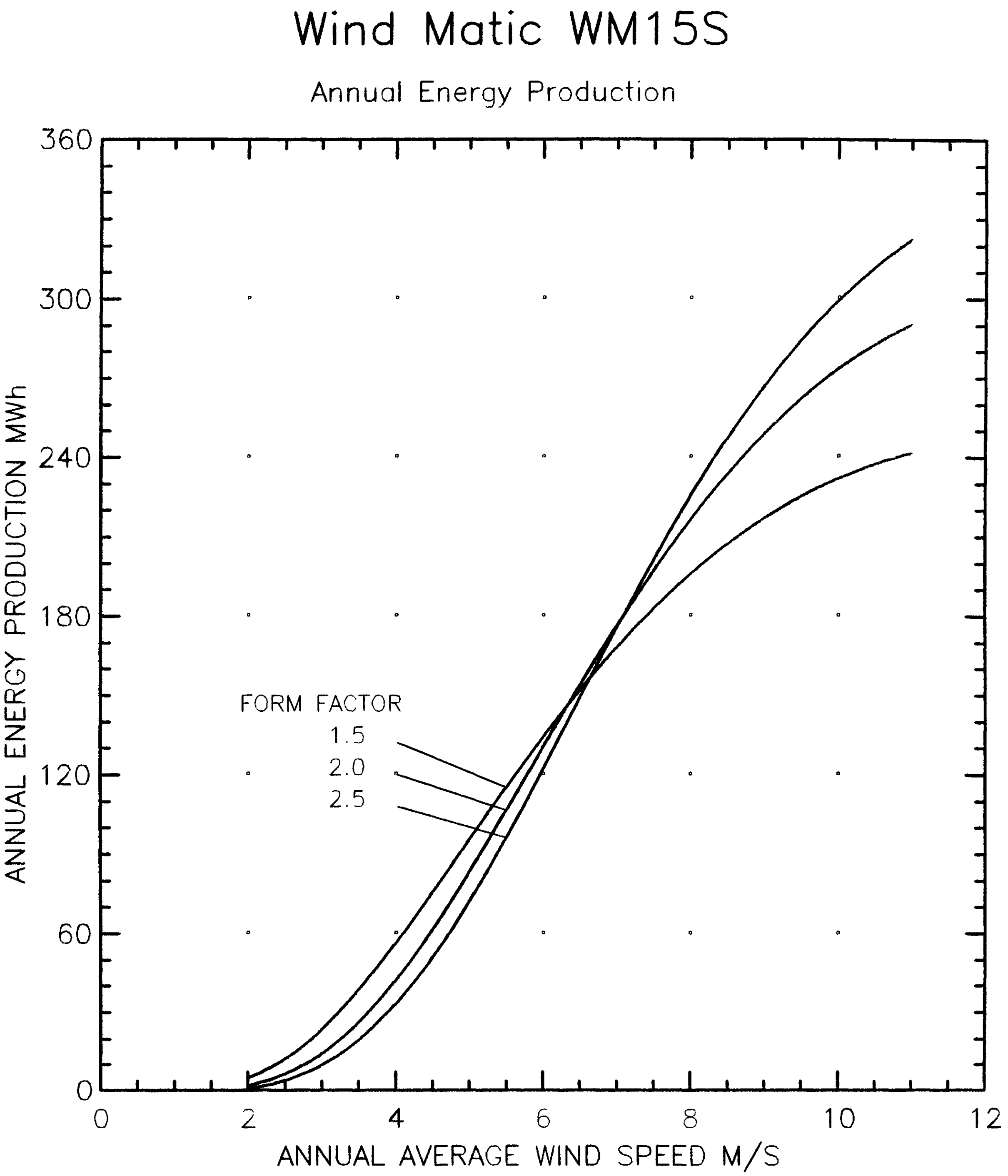
Annual energy production is calculated for a 100% availability and with the power curve data from chapter 5.1. The power output between the highest measured wind speed and the stop wind speed is considered the same as at the highest measured wind speed.

Calculation of the annual energy production is based on Weibull distributions, which for a form factor of two equals the Reyleigh distribution (see Ref. 1). The calculation is divided into two different categories. One deals with world wide application, where the annual mean wind speed is related to the hub height and five different form factors. For other form factors the annual energy production can be interpolated between the data given in Fig. 5.2.1 and Table 5.2.1.

For Danish application the wind atlas method is used (see Ref. 5). The annual energy production is calculated for the four clean roughness classes 0, 1, 2 and 3 at a wide range of hub heights and the data is presented in Table 5.2.2. For the actual 22 m hub height of the tested wind turbine the annual energy production at roughness class 0 is calculated to 199 MWh and correspondingly for class 1, 2 and 3 to 144 MWh, 112 MWh and 65 MWh.

For a specific site the terrain should be divided into eight direction sectors and analyzed separately as showed in the wind atlas. For wind speed distributions other than the Weibull distribution a specific calculation must be made.

A summary of the performance measurements is shown in Fig. 5.2.2.



TURBINE DATA

Rotor diameter 15.56 m   Rotational speed 39 and 55 rpm

Swept area 190 2 m**2   Tip angle 3.0, 3.2 and 3.5 deg

The annual energy production is calculated on basis of a measured power curve. Stop wind speed is 25.0 m/s
A 100% availability of the turbine is assumed

RISØ THE TEST STATION FOR WINDMILLS

Drawn: 05-DEC-85   Report: RISO-M-2481

Fig. 5.2.1. Energy production for Wind Matic WM 15S for different mean wind speeds and form factors.

Table 5.2.1 Energy production for different average wind speeds and form factors.

WIND TURBINE: Wind Matic WM15S REPORT: RISO-M-2481

ANNUAL ENERGY PRODUCTION

AV. WIND SPEED		FORM FACTORS 1.50	1.75	2.00	2.25	2.50
m/s	mph	(KWH)	(KWH)	(KWH)	(KWH)	(KWH)
2.0	4.5	4,759	2,945	1,893	1,249	842
2.5	5.6	12,130	8,559	6,304	4,802	3,750
3.0	6.7	23,527	18,037	14,290	11,696	9,832
3.5	7.8	38,532	31,498	26,227	22,384	19,559
4.0	8.9	56,236	48,512	42,083	37,052	33,195
4.5	10.1	75,564	68,224	61,366	55,530	50,781
5.0	11.2	95,516	89,594	83,213	77,230	72,000
5.5	12.3	115,282	111,608	106,581	101,237	96,143
6.0	13.4	134,260	133,418	130,449	126,489	122,219
6.5	14.5	152,035	154,380	153,944	151,955	149,134
7.0	15.7	168,343	174,043	176,403	176,758	175,857
7.5	16.8	183,035	192,115	197,368	200,239	201,534
8.0	17.9	196,051	208,424	216,552	221,955	225,532
8.5	19.0	207,397	222,887	233,798	241,646	247,448
9.0	20.1	217,123	235,488	249,036	259,194	267,071
9.5	21.3	225,315	246,259	262,257	274,568	284,335
10.0	22.4	232,074	255,270	273,494	287,794	299,267
10.5	23.5	237,519	262,618	282,815	298,928	311,945
11.0	24.6	241,767	268,417	290,309	308,047	322,461

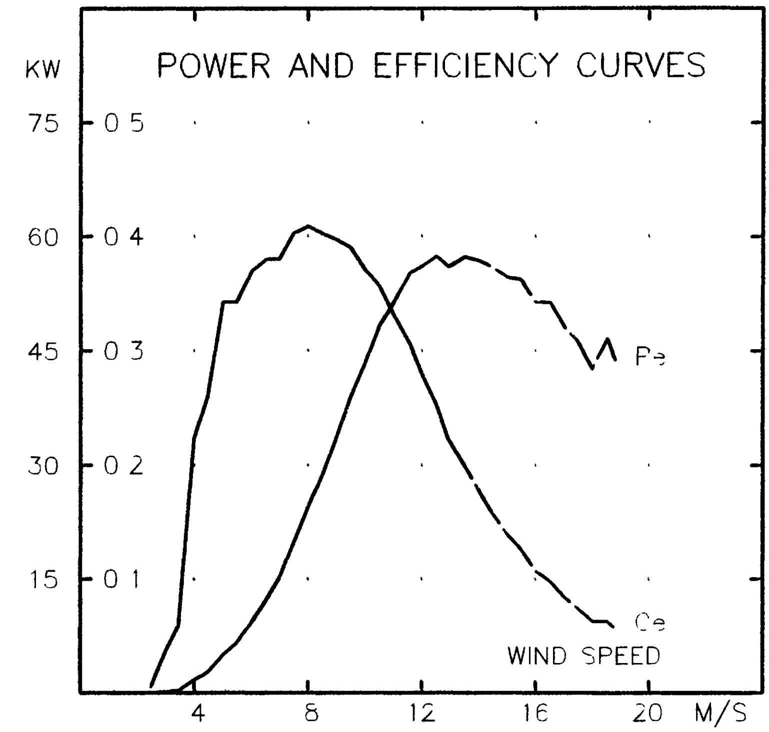
Table 5.2.2. Energy production for different roughness classes and hub heights.

WIND TURBINE: Wind Matic WM15S REPORT: RISO-M-2481

ANNUAL ENERGY PRODUCTION

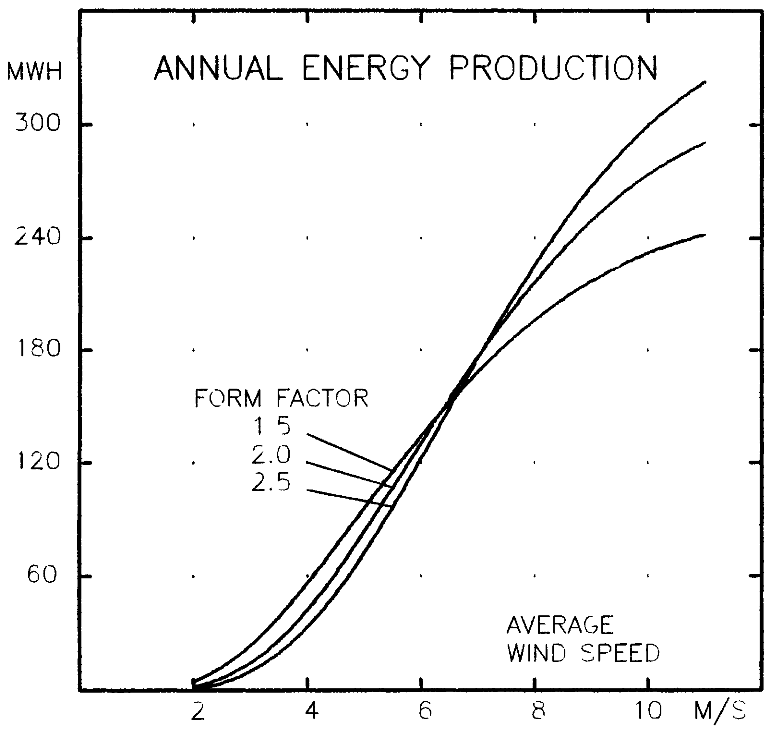
ROUGHNESS CLASS	0	1	2	3
HUB HEIGHT (M)	(KWH)	(KWH)	(KWH)	(KWH)
18	193,835	135,345	102,826	56,198
19	195,265	137,629	105,301	58,570
20	196,612	139,797	107,659	60,856
21	197,885	141,861	109,912	63,062
22	199,092	143,829	112,068	65,191
23	200,237	145,709	114,134	67,250
24	201,328	147,510	116,119	69,243
25	202,368	149,237	118,028	71,173
26	203,452	151,073	120,019	73,200
27	204,490	152,837	121,938	75,166
28	205,485	154,534	123,789	77,077
29	206,441	156,169	125,577	78,935
30	207,360	157,745	127,306	80,741

Wind Matic WM15S



V (M/S)	Pe (KW)	Ce
2.48	0 01	0 006
3.02	0 12	0 037
3.45	0 28	0 059
4.01	1 68	0 224
4 47	2.71	0 260
5.01	5.02	0 343
5.49	6 60	0 342
6 02	9 40	0 370
6 52	12.26	0 380
6 98	15.06	0 380
7.49	19 70	0 402
8 00	24.37	0 409
8 47	28 51	0 403
9 00	33.68	0 397
9 49	38.86	0 390
10 01	43.28	0 370
10 51	48 26	0 357
11.00	51.39	0 331
11.57	55.21	0 306
12.04	56 22	0 276
12.50	57.44	0 252
12.93	56 03	0 222
(13.50)	(57.28)	(0 200)
(13.99)	(56 76)	(0 178)
(14 46)	(55.98)	(0 159)
(15.00)	(54.59)	(0 139)
(15.50)	(54.25)	(0 125)
(16 01)	(51.39)	(0 107)
(16 52)	(51.28)	(0 098)
(17.03)	(47.95)	(0 083)
(17.46)	(46 27)	(0 075)
(17.99)	(42.61)	(0 063)
(18.52)	(46 60)	(0 063)
(18.89)	(43.10)	(0 055)

VSTOP= 25.0 M/S



RISØ THE TEST STATION FOR WINDMILLS

Drawn: 05–DEC–85 Report: RISO–M–2481

Fig. 5.2.2. Summary of performance measurements.

5.3 Transmission efficiency

The power train idling for motor without the rotor was measured in the Test Station´s workshop. The surrounding temperature was 12 deg(C).

At first, the small generator was coupled to the grid, and the absorbed power for cold condition was 4.2 kW. After 3.5 hours the absorbed power was constantly 3.5 kW and the gearbox oil temperature 31 deg(C).

Immediately afterwards, the large generator was coupled to the grid. The absorbed power was now 5.3 kW, and after 2 hours operation the power dropped to 4.7 kW for an oil temperature of 40 deg(C).

The transmission efficiency of the turbine in operation was measured as described in chapter 3.2. The bin parameter was the wind speed. Measurements were performed from 1/2-85 to 4/2-85, totalling 64 hours of measurement time. The result is shown in Fig. 5.3.1 and in Table 5.3.1.

The maximum transmission efficiency is 85.0% at 35.9 kW electric power, and below 20 kW the efficiency drops off. In the region up to about 10 kW the turbine operates on the small generator, and there is a peak efficiency of 81.3% at 5.3 kW. Care should be taken not to draw too wide conclusions in the region where the generators shifts between one another. No analysis has been made to distinguish between operation on the two generators.

5.4 Rotor Performance.

The power delivered from the rotor shaft to the nacelle is an expression of how good the wind turbine blades are to extracts the energy from the wind.

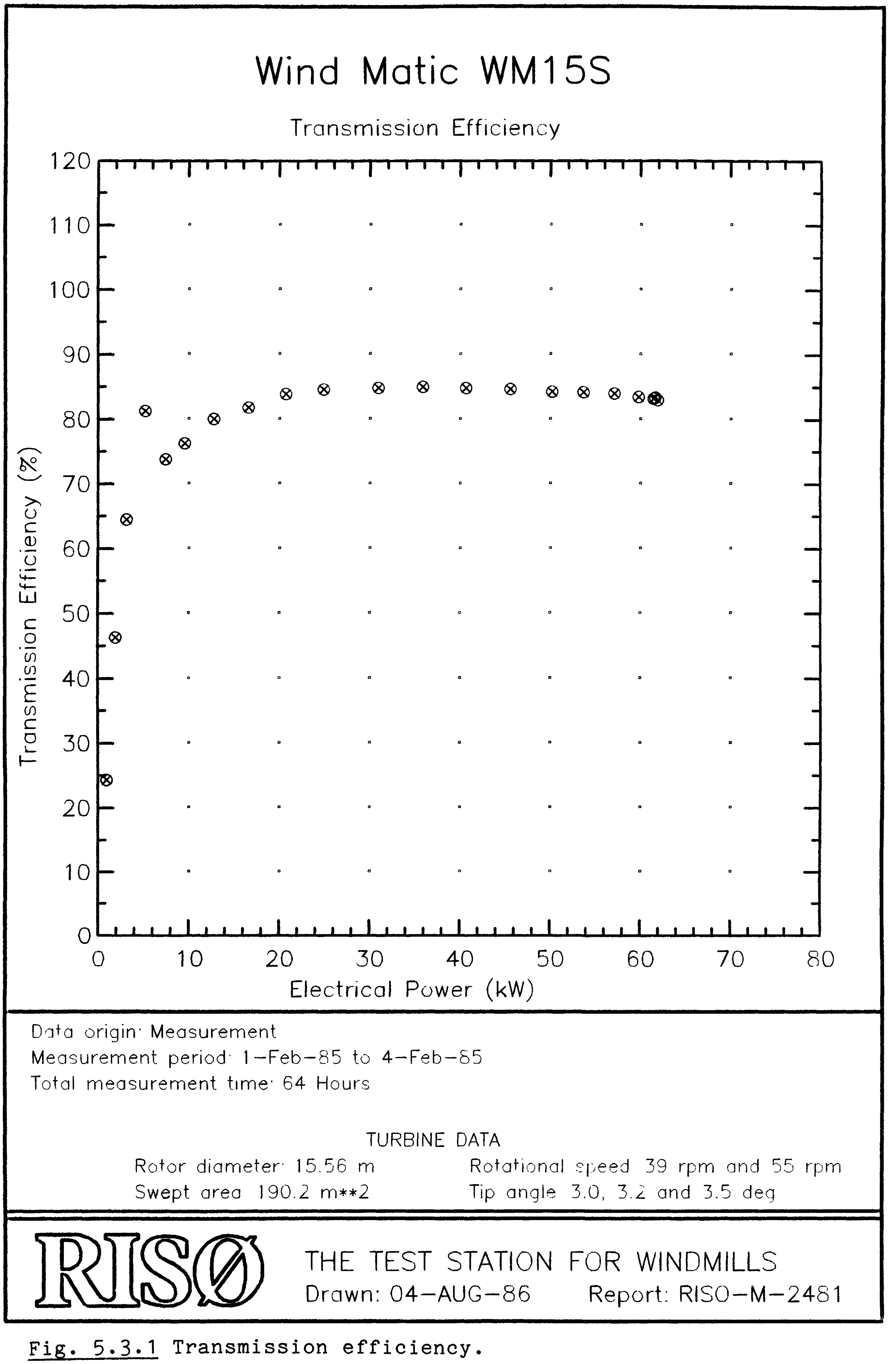


Fig. 5.3.1 Transmission efficiency.

Table 5.3.1 Tabulated data for transmission efficiency.

Wind Matic WM15S RISO-M-2481

ROTOR DIAMETER (M): 15.56 m
SWEPT AREA (M**2): 190.2 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 3.0, 3.2 and 3.5 deg
MEASUREMENT PERIOD: 1-Feb-85 to 4-Feb-85
MEASUREMENT TIME: 64 Hours

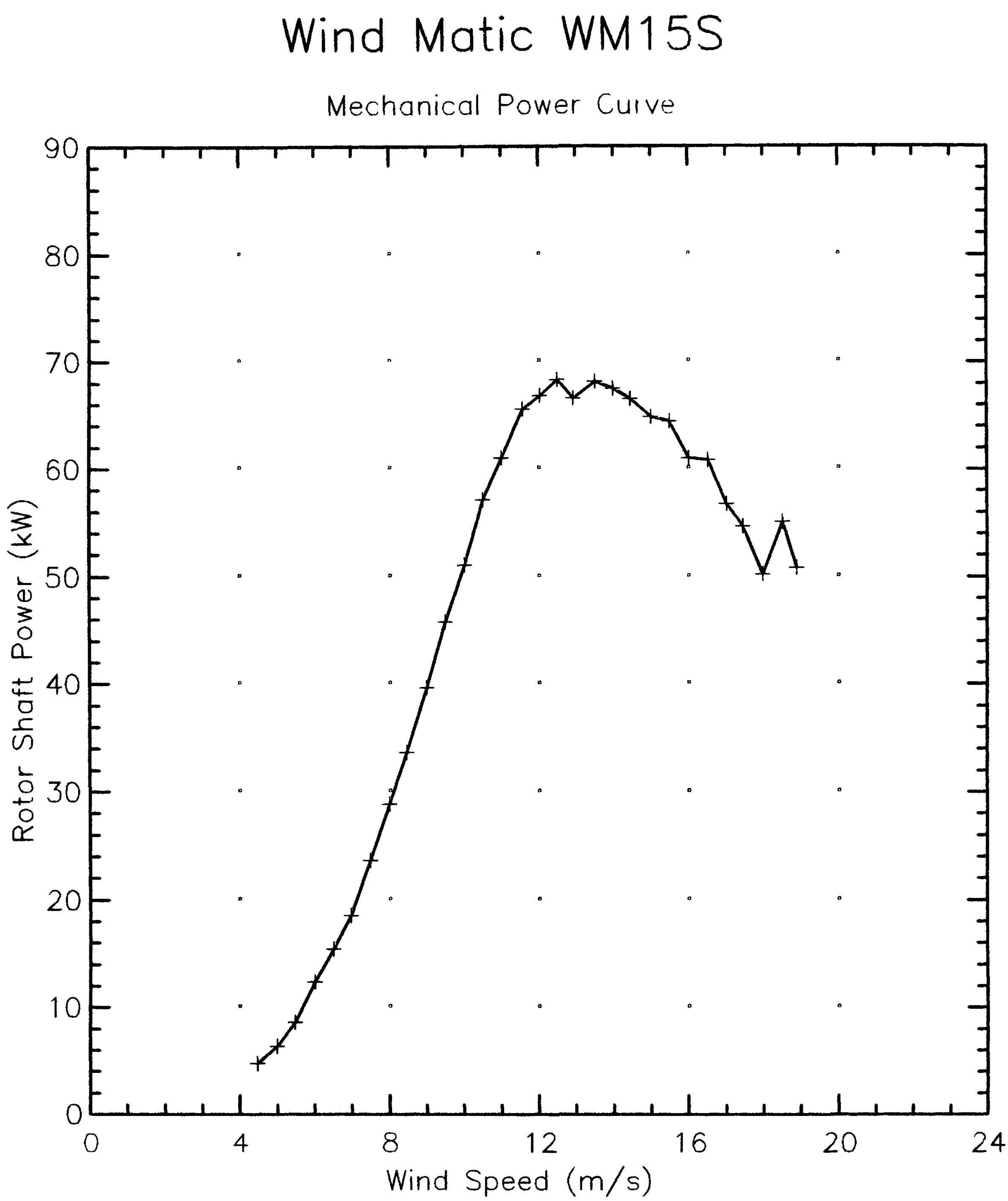
MEASURED DATA CURVE: Transmission Efficiency

X: Electrical Power (kW)
Y: Transmission Efficiency (%)

	X	Y
1	0.95	24.300
2	1.98	46.300
3	3.19	64.500
4	5.27	81.300
5	7.47	73.800
6	9.62	76.300
7	12.82	80.100
8	16.60	81.800
9	20.74	83.900
10	24.93	84.600
11	30.97	84.900
12	35.90	85.000
13	40.67	84.900
14	45.62	84.700
15	50.21	84.300
16	53.70	84.200
17	57.16	84.100
18	59.82	83.500
19	61.49	83.300
20	61.66	83.400
21	61.95	83.000

The rotor shaft power is calculated from the measurements of the power curve and the transmission efficiency. A linear interpolation is used for the transmission efficiency. The mechanical power curve is shown in Fig. 5.4.1. and the data are tabulated in Table 5.4.1. The corresponding rotor efficiency is shown in Fig. 5.4.2 and the data tabulated in Table 5.4.2.

The maximum efficiency is 48.7% at 6 m/s. This point might be coinciding with the change from one generator to the other and therefore it is more likely that the rotor itself has an optimum at 8 m/s where the efficiency is 48.4%. The maximum power output is 68.4 kW at a wind speed of 12.5 m/s.



Data origin: Calculated from measured Power and Transmission Efficiency Curves

TURBINE DATA

Rotor diameter 15.56 m
Swept area 190.2 m**2
Rotational speed 39 rpm and 55 rpm
Tip angle 3.0 3.2 and 3.5 deg

RISØ THE TEST STATION FOR WINDMILLS

Drawn: 05-DEC-85 Report: RISO-M-2481

Fig. 5.4.1 Mechanical power curve.

Table 5.4.1 Tabulated data for mechanical power curve.

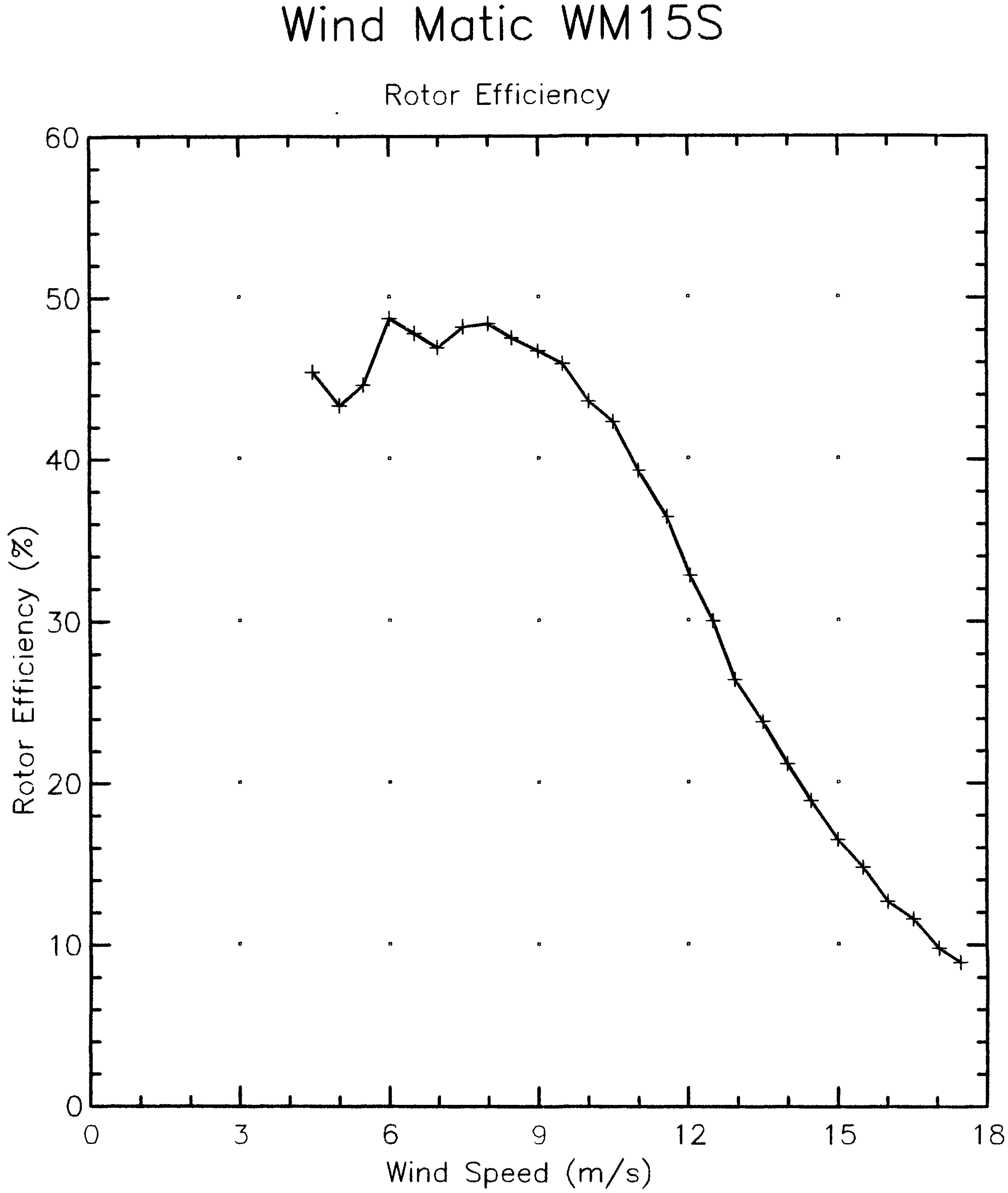
Wind Matic WM15S RISO-M-2481

ROTOR DIAMETER (M): 15.56 m
SWEPT AREA (M**2): 190.2 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 3.0, 3.2 and 3.5 deg
MEASUREMENT PERIOD: Calculated from m. data
MEASUREMENT TIME: None

MEASURED DATA CURVE: Mechanical Power Curve

X: Wind Speed (m/s)
Y: Rotor Shaft Power (kW)

	X	Y
1	4.47	4.730
2	5.01	6.330
3	5.49	8.600
4	6.02	12.360
5	6.52	15.430
6	6.98	18.570
7	7.49	23.630
8	8.00	28.840
9	8.47	33.630
10	9.00	39.650
11	9.49	45.750
12	10.01	51.040
13	10.51	57.130
14	11.00	60.990
15	11.57	65.600
16	12.04	66.830
17	12.50	68.350
18	12.93	66.600
19	13.50	68.130
20	13.99	67.480
21	14.46	66.540
22	15.00	64.850
23	15.50	64.440
24	16.01	60.990
25	16.52	60.850
26	17.03	56.750
27	17.46	54.670
28	17.99	50.240
29	18.52	55.070
30	18.89	50.820



Data origin: Calculated from Mechanical Power Curve

TURBINE DATA

Rotor diameter 15.56 m

Swept area 190 2 m**2

Rotational speed 39 rpm and 55 rpm

Tip angle 3.0, 3.2 and 3.5 deg

RISØ THE TEST STATION FOR WINDMILLS

Drawn: 05-DEC-85 Report: RISO-M-2481

Fig. 5.4.2 Rotor efficiency

Table 5.4.2 Tabulated data from rotor efficiency.

Wind Matic WM15S RISO-M-2481

ROTOR DIAMETER (M): 15.56 m
SWEPT AREA (M**2): 190.2 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 3.0, 3.2 and 3.5 deg
MEASUREMENT PERIOD: Calculated from m. data
MEASUREMENT TIME: None

MEASURED DATA CURVE: Rotor Efficiency

X: Wind Speed (m/s)
Y: Rotor Efficiency (%)

	X	Y
1	4.47	45.400
2	5.01	43.300
3	5.49	44.600
4	6.02	48.700
5	6.52	47.800
6	6.98	46.900
7	7.49	48.200
8	8.00	48.400
9	8.47	47.500
10	9.00	46.700
11	9.49	45.900
12	10.01	43.600
13	10.51	42.300
14	11.00	39.300
15	11.57	36.400
16	12.04	32.800
17	12.50	30.000
18	12.93	26.400
19	13.50	23.800
20	13.99	21.200
21	14.46	18.900
22	15.00	16.500
23	15.50	14.800
24	16.01	12.700
25	16.52	11.600
26	17.03	9.800
27	17.46	8.900

5.5 Power quality.

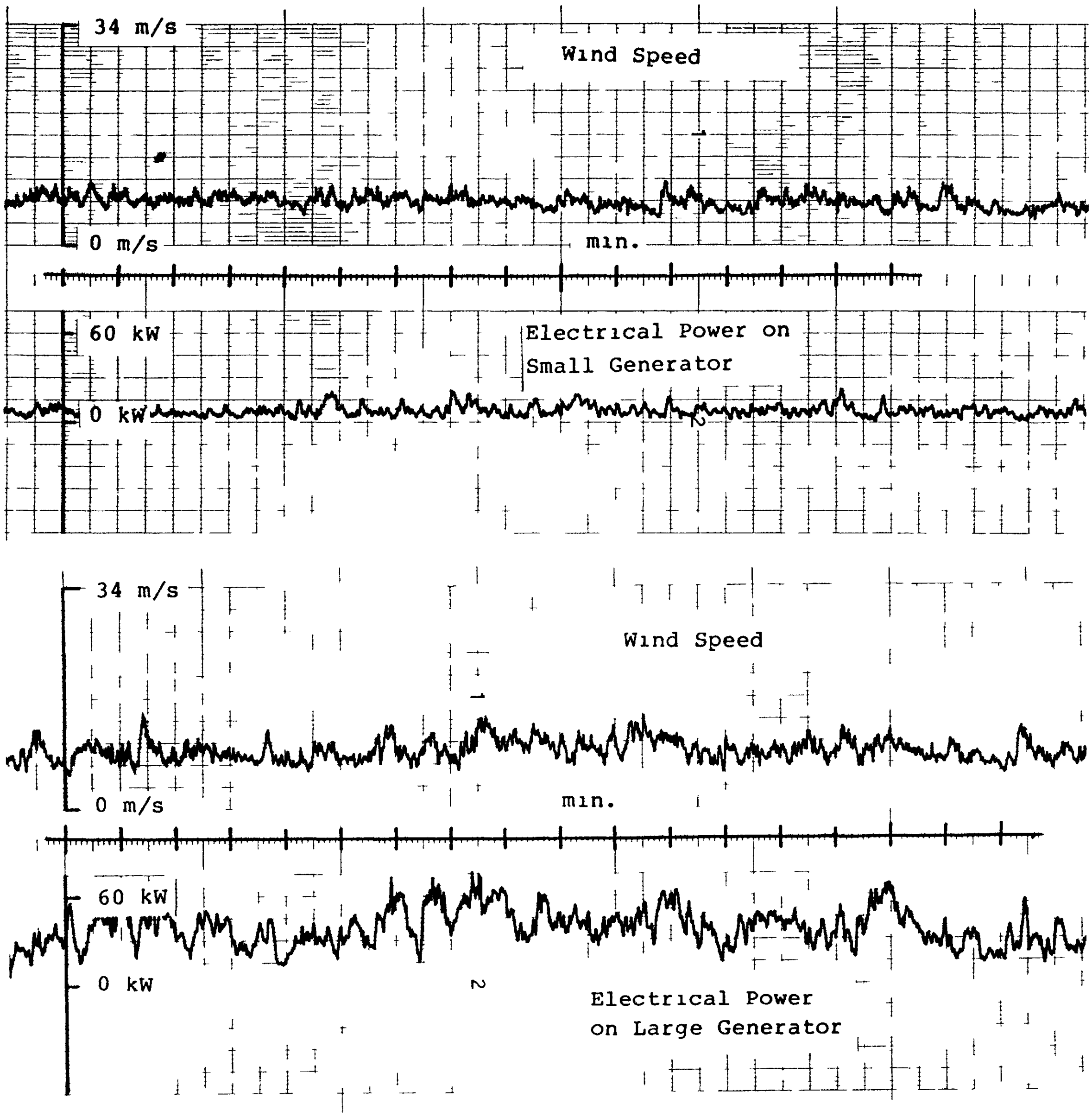
The power quality is described through time tracks, frequency spectra, and cut-in measurements.

The time tracks in Fig. 5.5.1 show that when the turbine operates on the small generator power peaks up to 21 kW are reached. On the large generator power peaks up to 76 kW are reached. The largest power gradient seem to be 42 kW in about 4 sec. The time track was recorded at a wind speed where the wind turbine nearly has reached the stalled condition. This area must be expected to contain the largest power fluctuations.

The frequency spectra in Fig. 6.1.4 show pronounced frequency content at 0.92 Hz, which is the rotor rotational frequency, and at 1.76 Hz, which is very close to the double of the rotational frequency. At three times the rotational frequency, i.e. the blade frequency, very little vibrational energy is passed through to the electric grid. Above 3.5 Hz the frequency content is negligible. Concerning grid loads at the cut-in sequence chapter 6.2 describes the grid current.

Wind Matic WM15S

Electrical Power



TURBINE DATA

Rotor diameter 15 56 m   Rotational speed 39 rpm and 55 rpm
Swept area 190 2 m**2   Tip angle 3 0, 3 2 and 3 5 deg

RISØ THE TEST STATION FOR WINDMILLS
Drawn 31-JAN-86   Report RISO-M-2481

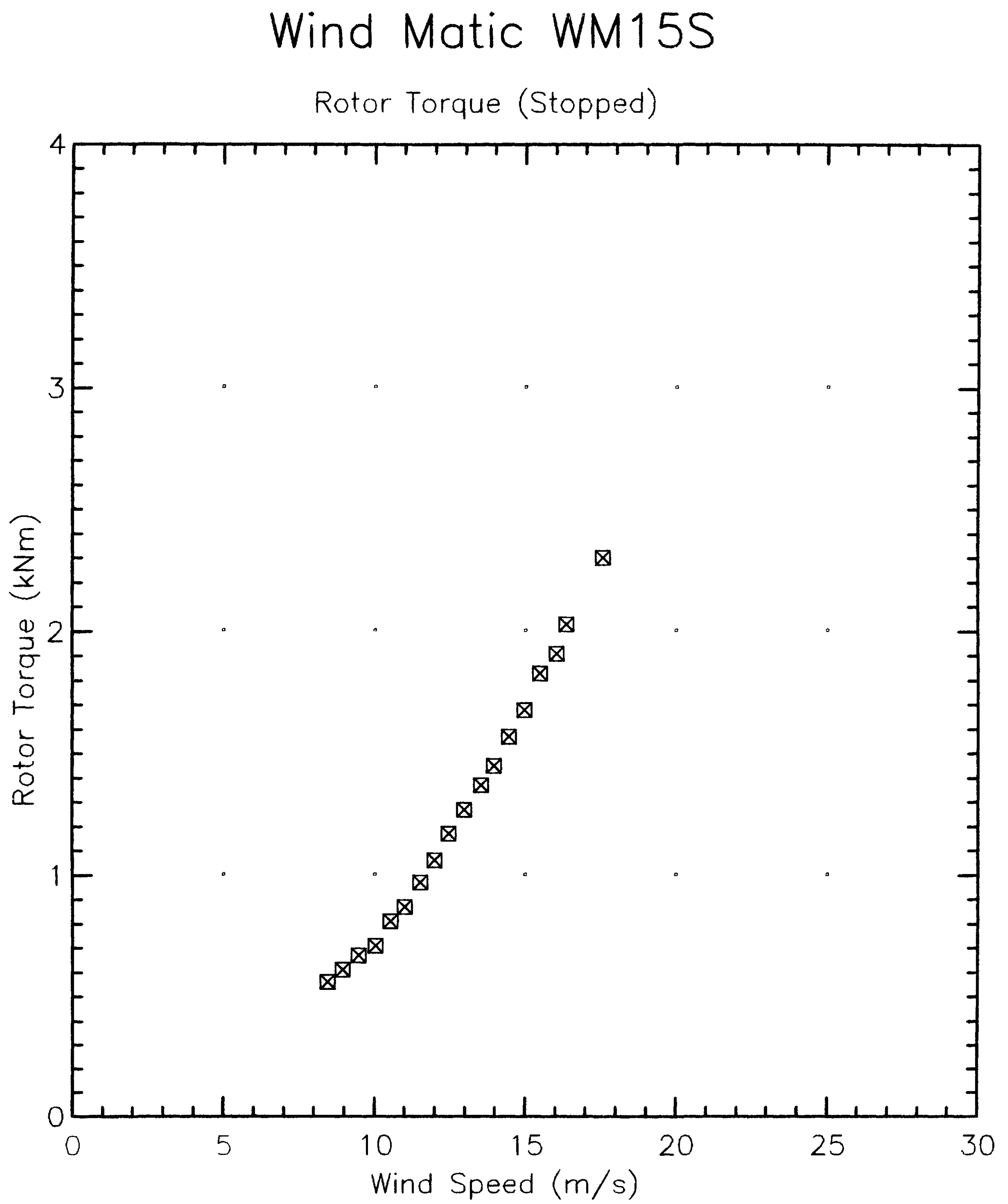
Fig. 5.5.1 Power fluctuations.

5.6 Rotor torque at standstill.

The start up conditions for the turbine are important because a lot of energy can be lost at the lower wind speeds if no special care has been taken to this point.

Fig. 5.6.1 shows the measured rotor torque at standstill. It was measured at high wind speeds, but the curve can be extrapolated because it fits a second order polynomium. The corresponding data are given in Table 5.6.1.

The turbine had no problems with the start up conditions. Electric motoring on the small generator was employed in the control system for situations where the rotor not did start by itself. An anemometer monitored these conditions, and the system worked very well.



Data origin: Measurement
Measurement period 30-Jan-85
Total measurement time 4 Hours

TURBINE DATA

Rotor diameter 15.56 m	Rotational speed 39 rpm and 55 rpm
Swept area 190.2 m**2	Tip angle 3.0, 3.2 and 3.5 deg

RISØ THE TEST STATION FOR WINDMILLS
Drawn: 09-DEC-85 Report: RISO-M-2481

Fig. 5.6.1 Rotor torque of standstill.

Table 5.6.1 Data for rotor torque at standstill.

Wind Matic WM15S RISO-M-2481

ROTOR DIAMETER (M): 15.56 m
SWEPT AREA (M**2): 190.2 m**2
ROTATIONAL SPEED (RPM): 39 rpm and 55 rpm
TIPANGLE (DEG): 3.0, 3.2 and 3.5 deg
MEASUREMENT PERIOD: 30-Jan-85
MEASUREMENT TIME: 4 Hours

MEASURED DATA CURVE: Rotor Torque (Stopped)

X: Wind Speed (m/s)
Y: Rotor Torque (kNm)

	X	Y
1	8.47	0.561
2	8.95	0.610
3	9.50	0.670
4	10.05	0.710
5	10.54	0.810
6	11.01	0.870
7	11.53	0.970
8	11.99	1.060
9	12.48	1.170
10	12.98	1.270
11	13.54	1.370
12	13.97	1.450
13	14.47	1.570
14	14.98	1.680
15	15.49	1.830
16	16.05	1.910
17	16.37	2.030
18	17.58	2.300

6. STRUCTURAL MEASUREMENTS.

Structural measurements are restricted to measurements of vibrations in the construction with very few sensors, and loads at cut-in.

6.1 Structural dynamics

The vibrations in the construction were measured with strain-gauge bridges mounted for the edgewise and flapwise root bending moments in one blade and the rotor torque on the main shaft.

Frequency spectra were measured for the following conditions.

1. The wind turbine was stopped with the rotor towards the free wind. The blade was set in four positions, vertical upwards, horizontal with the leading edge downwards, vertical downwards and horizontal with the trailing edge downwards.

2. The wind turbine operating on the large generator.

The measurements according to point 1 are used for determining eigenfrequencies in the structure. All vibrations originating from the rotation can be eliminated while the turbulence in the air is the only excitating force on the structure. These measurements indicate a tower bending mode frequency of 1.68 Hz, a torsional tower mode frequency of 2.24 Hz and a flapwise asymmetric rotor mode frequency of 2.64 Hz. The flapwise symmetric rotor mode, i.e. the flapwise blade eigenfrequency, is 3.20 Hz.

The edgewise blade eigenfrequency is 6.64 Hz.

Figure 6.1.1 shows the flapwise and edgewise bending moment at the blade root when the turbine operates on the large generator at a wind speed of approximately 8 m/s. Figure 6.1.2 shows the same but with the amplitudes enlarged for analysis of the frequency content.

It is clearly seen that the dominant frequency both flapwise and edgewise is the rotational frequency of 0.91 Hz. The frequencies 1.84, 2.72 and 3.68 Hz are 2 p, 3 p and 4 p respectively.

There is some flapwise vibrational energy in the frequency range from 1.84 (2 p) to 3.20 Hz (flapwise blade eigenfrequency), but it is remarkable that the frequency response around the 3 p frequency (2.72 Hz) seems to be very well damped, although the flapwise asymmetric rotor mode (2.64 Hz) is very close to the excitational frequency due to tower shadow.

The eigenfrequencies 4.80 and 5.68 Hz are the drive train and edgewise asymmetric rotor modes respectively.

Generally speaking, the frequency spectra show a well damped blade where the dominant vibrational content lies in the rotational frequency. There is a high degree of coupling between the flapwise and edgewise bending moments.

Time traces for the two bending moments when operated on the small generator at 6-7 m/s are shown in Fig. 6.1.3.

Frequency spectra for the rotor torque and electric power are shown in Fig. 6.1.4 and 6.1.5 for a wind speed of about 10 m/s. Due to very good correlation between the two parameters the spectra are almost alike. 1 p is dominant in both spectra. The spectrum for rotor torque is having two peaks close to each other at 1.76 and 1.84 Hz while only the first is seen on the spectrum for electric power. All frequencies above 3.5 Hz are damped out in this last spectrum.

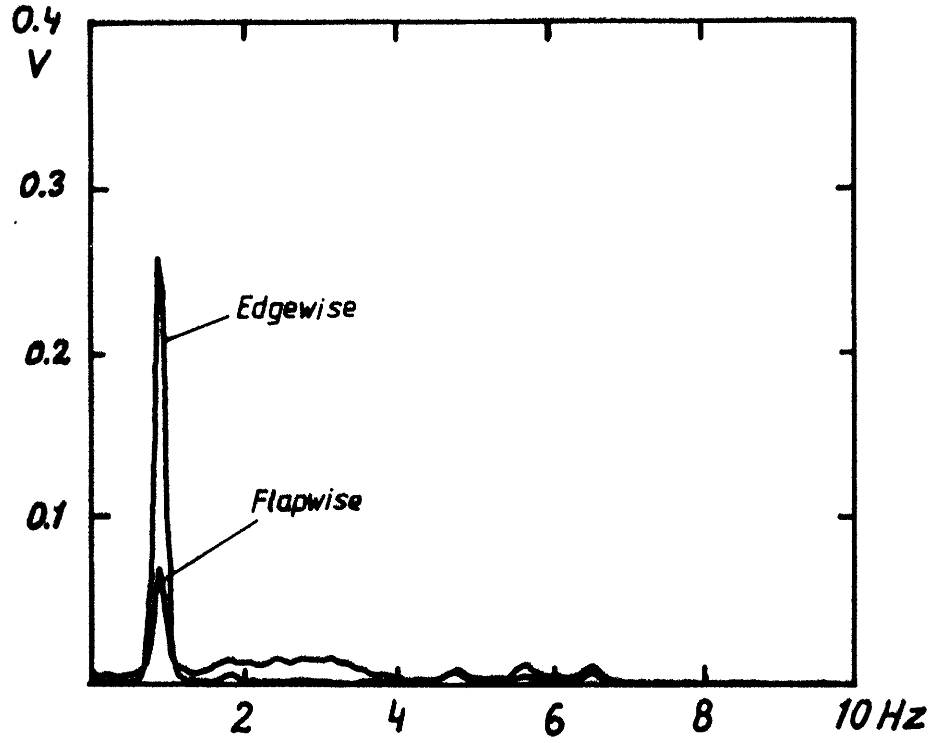


Fig. 6.1.1. Frequency spectra of flapwise and edgewise blade root bending moments when operating on large generator.

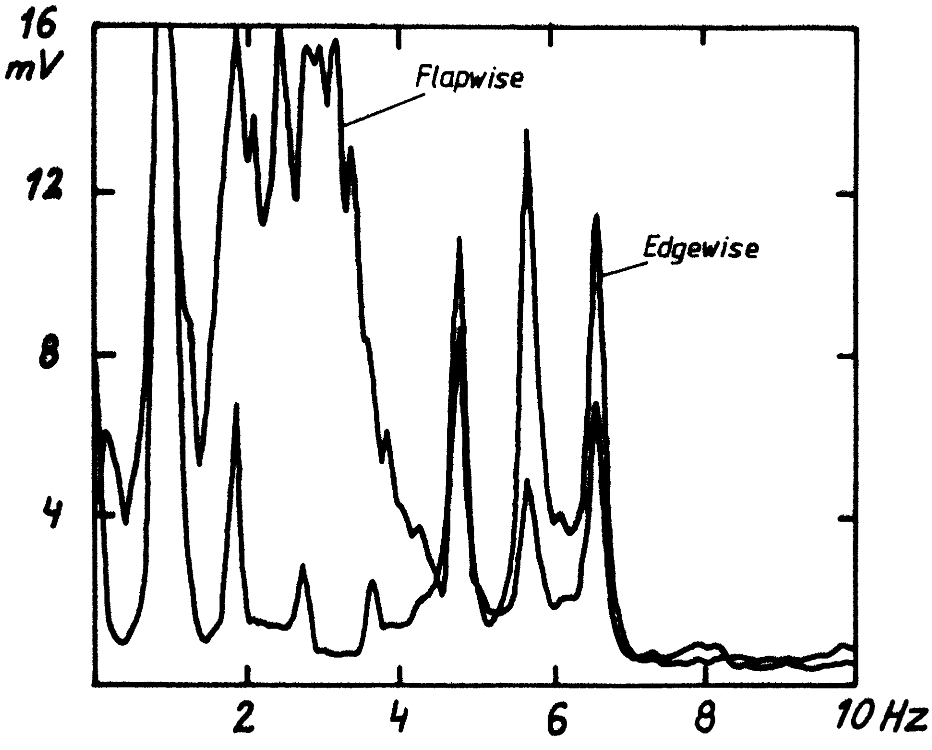


Fig. 6.1.2 Frequency spectra of flapwise and edgewise blade root bending moments (enlarged).

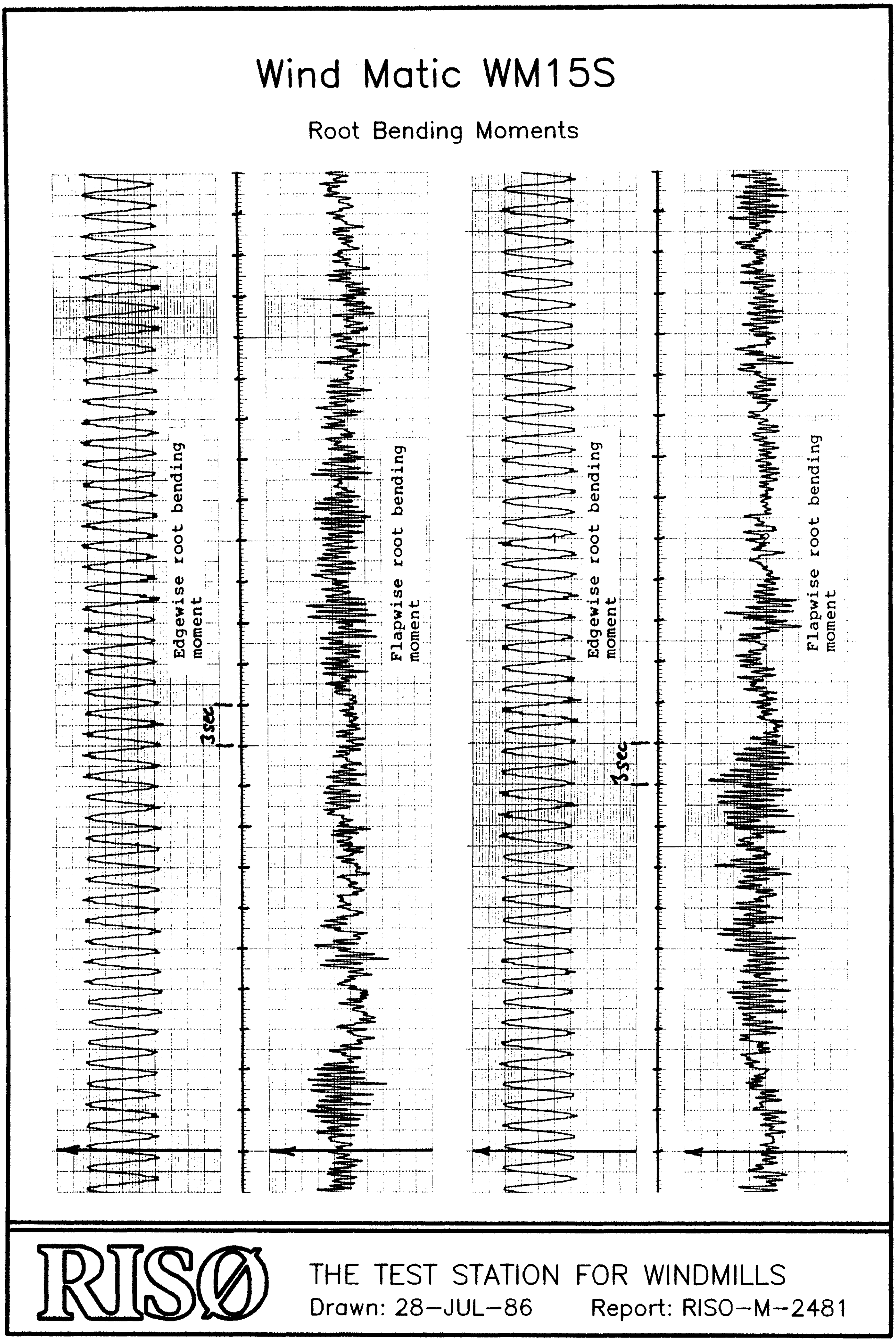


Fig. 6.1.3 Time traces of the blade root bending moments.

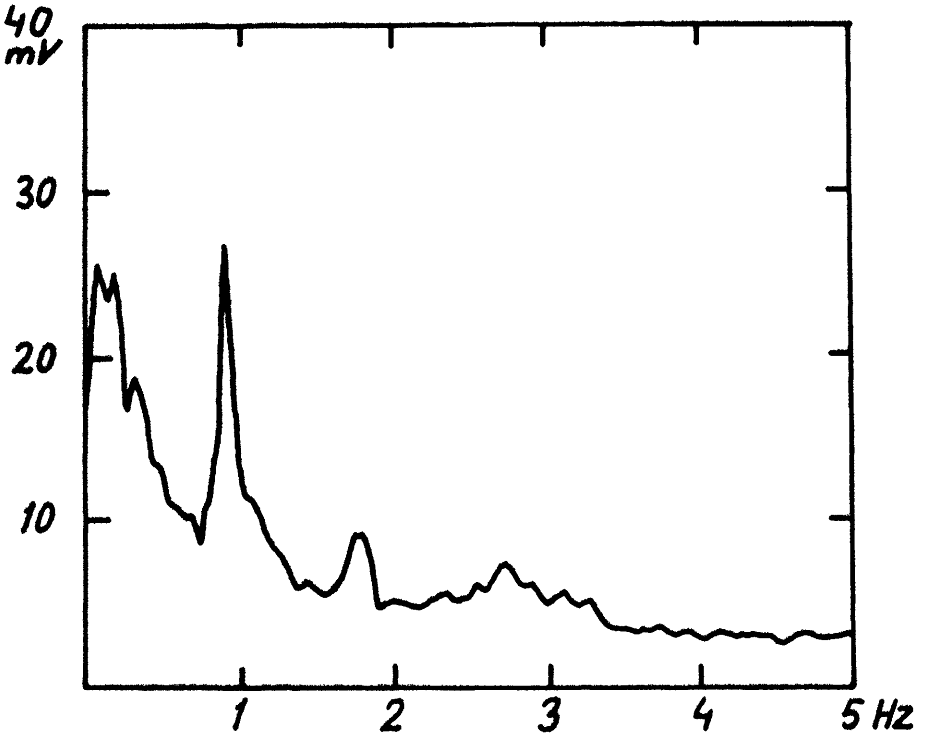


Fig. 6.1.4 Frequency spectrum of rotor torque.

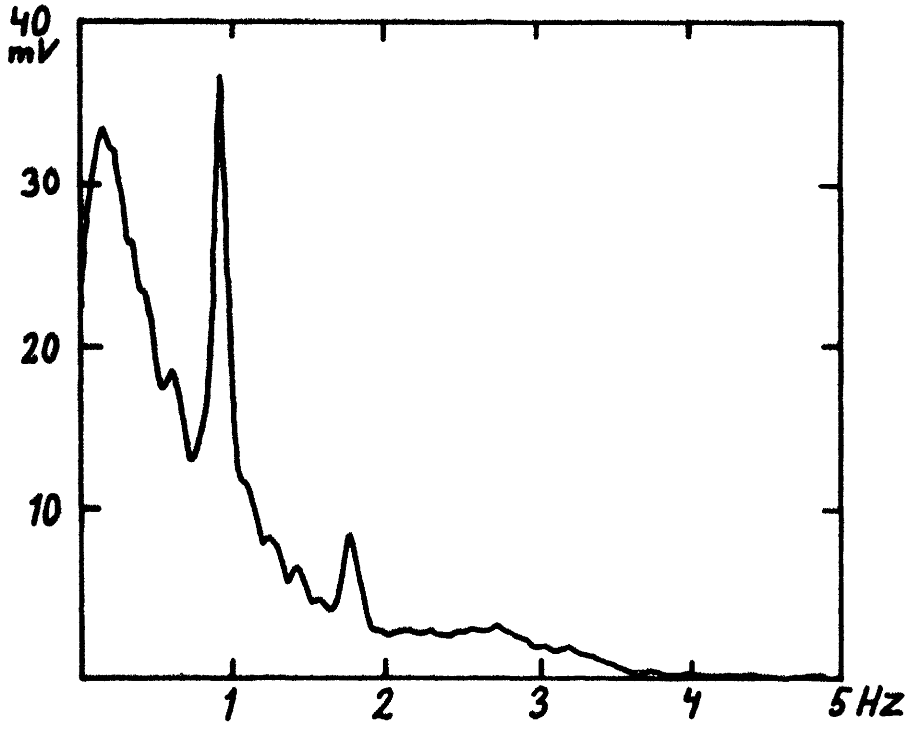


Fig. 6.1.5 Frequency spectrum of electric power.

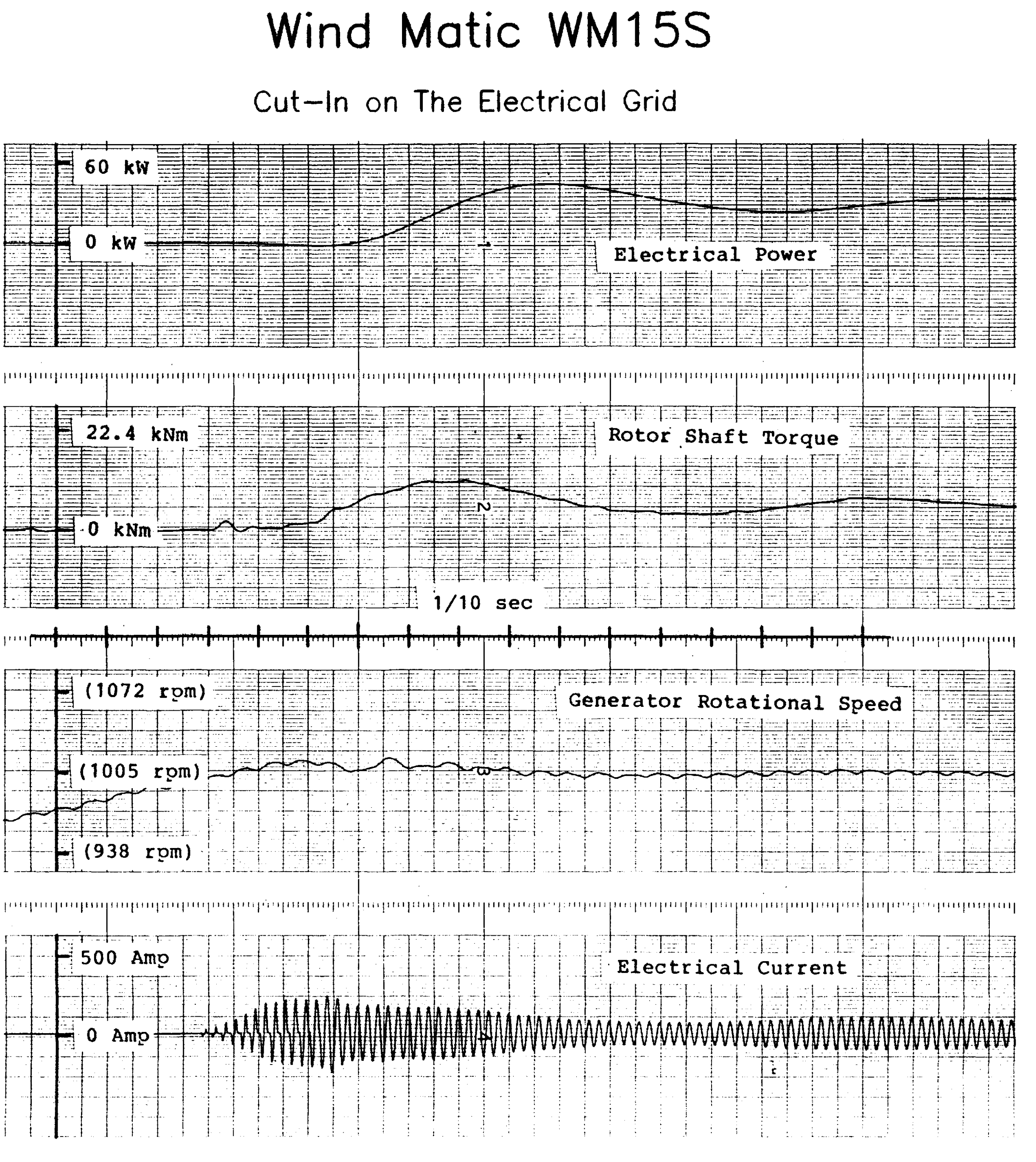
6.2 Loads at cut-in.

A cut-in sequence on the large generator at about 50% power is shown in Fig. 6.2.1. The signals for rotor shaft torque and electrical current on one phase are unfiltered while the electrical power and generator rotational speed are filtered with a 20 Hz low pass filter. The absolute figures for the rotational speed are not necessarily correct. Their level is estimated from the power on the generator after cut-in.

The rotor shaft torque raises to a maximum of 11.4 kNm during cut-in and the curve is very soft. This torque corresponds to 96% of the torque at full power with 68.4 kW delivered from the rotor. The torque might be less when cut-in is performed at normal power.

The electrical current has a maximum of 250 Amp in amplitude. This current corresponds to 172% the current at full power with 57.4 kW delivered from the generator when the calculation of the effective current is presuming a sinusoidal curve during the cut-in sequence, and a $\cos\varphi$ of 0.85.

The maximum cut-in current is relatively large, because it is an abnormal cut-in condition at 50% power. Smaller values must be expected at normal cut-in at about 25% power.



Cut–In sequence is measured for the large generator.
Measurement period: 23–Jan–85

TURBINE DATA

Rotor diameter: 15.56 m
Swept area: 190.2 m**2
Rotational speed: 39 rpm and 55 rpm
Tip angle: 3.0, 3.2 and 3.5 deg

RISØ THE TEST STATION FOR WINDMILLS
Drawn: 28–JAN–86 Report: RISO–M–2481

Fig. 6.2.1. Loads at cut-in.

7. ENVIRONMENTAL MEASUREMENTS

The wind turbine has a certain impact on the environments, and the most important part of this is the noise emission.

7.1 Noise emission.

The noise emission was measured by a subcontractor and the result is reported here.

The A-weighted sound pressure level was measured 1.5 m above the ground 20 m behind the wind turbine and also 20 m to the right of the rotor plane when facing the wind. The wind speed was registrered in 10 m height. The measurements were carried out the 28th-29th of June and the 9th of November 1984.

The measurements are shown in Appendix A.

BILAG 2 shows time traces of the W-weighted sound pressure level 20 m behind the turbine. BILAG 3 shows the A-weighted sound pressure levels as a function of the wind speed also behind the wind turbine. BILAG 4 shows a 3 db band analysis of the turbine running on the large generator (upper curve) and stopped (lower curve). BILAG 5 shows the same, but operating on the small generator (lower curve). BILAG 6 shows the same, but with a 1/3 octave band analysis.

SUMMARY

The standard test comprised tests of the safety systems: mechanical and air brakes. The mechanical brake was tested at maximum power by disconnecting the main switch and the rotor was stopped after a safe brake sequence. The brake torque was almost constant at 199% the maximum operational rotor torque and the cut-in of the brake was well damped, eliminating high transient loads. The efficiency of the air brakes was measured for a free running rotor and the normal rotational speed of 55 rpm was reached at 16 m/s. At higher wind speeds the rotational speed is expected to rise proportional. At 30 m/s the rotational speed is expected to be 101 rpm, which is very high.

The performance measurements show a maximum overall efficiency of 40.9% at 8.0 m/s and a maximum power of 57.4 kW at 12.5 m/s. The power regulation by stall is efficiently lowering power at higher wind speeds. The calculated energy production shows 83, 130 and 176 MWh for Rayleigh distributed wind speeds with annual mean wind speeds of 5, 6 and 7 m/s. The corresponding annual energy productions per square meter are 437, 685 and 927 kWh/m^2.

The maximum transmission efficiency is 85.0% at about 36 kW and below 20 kW the efficiency drops of. The maximum rotor efficiency is 48% at 8 m/s. Power fluctuations were relatively high, showing power increase of 10.5 kW/sec during 4 seconds. The rotor had no starting problems due to an efficient and reliable start up mechanism.

The construction is generally well damped and no eigenfrequencies seem to be periodically excitated to give dangerous unstable structural dynamics.

The torque at cut-in lies below the nominal operational torque. The max. transient current however, is about 70% more than that at full power, but the measurement was carried out at an unnormal cut-in condition at 50% nominal power.

The noise level was found as about 54 dB (A) at 9 m/s at a distance of 20 m from the windmill.

REFERENCES

1. "Guidance for Test of Wind Turbines" (Danish). Troels Friis Pedersen, September 1985.

2. "Recommended Practices for Wind Turbine Testing and Evaluation. 1 Power Performance Testing". IEA 1982.

3. "WM 15S Manual, type 0. November 1984

4. "Standard measurements on windmills at The Test Station for Windmills at Risø, Denmark"
Troels Friis Pedersen, 1983.

5. "Wind Atlas for Denmark"
Erik Lundtang Petersen, Ib troen, Steen Frandsen, 1980.

APPENDIX A: MEASUREMENTS OF NOISE EMISSION

STØJMÅLINGER

Mølletype:	Windmatic 55 kW
Målested:	Prøvestationen for mindre vindmøller, Risø
Måleperiode:	28.-29. juni og 9. november 1984.

BESKRIVELSE AF MÅLELOKALITET

Møllen var placeret på et af prøvestationens dertil indrettede fundamenter.

Terrænet omkring møllen var nogenlunde fladt, med et fald fra øst mod vest. På arealet omkring møllen var der i møllens læside en mark med 80 cm højt korn, mens der i møllens vingeplan var arealer med kortklippet græs.

I en afstand af ca. 150 m fra møllen ligger landevejen til Roskilde, hvorfra en væsentlig fremmedstøj, i form af trafikstøj, kom.

BESKRIVELSE AF MÅLINGER

Der blev udført registrering af det A-vægtede lydtrykniveau 1,5 m over terræn i følgende punkter:

P1: 20 meter fra møllefoden i læsiden.
P2: 20 meter fra møllefoden i vingeplanet.

Endvidere blev vindhastigheden registreret i 10 meters højde.

En situationsplan med angivelse af målepunkternes placering findes på bilag 1.

Under målingerne kørte møllen dels på den lille generator ved lav vindhastighed, dels på den store generator ved højere vindhastigheder.

BESKRIVELSE AF METEOROLOGISKE FORHOLD

Under målingerne forekom der vindhastigheder i intervallet 3 m/s - 10 m/s. Vindretningen var vestlig d. 28.-29. juni og østlig den 9. november.

MÅLEUDSTYR

Følgende typer måleinstrumenter blev anvendt ved målinger og analyser.

1/2" mikrofon	type 4165	fabrikat Brüel & Kjær
Statistisk analysator	type 4426	fabrikat Brüel & Kjær
Alfanumerisk printer	type 2312	fabrikat Brüel & Kjær
Niveauskriver	type 2306	fabrikat Brüel & Kjær
Lydtrykmåler	type 2209	fabrikat Brüel & Kjær
Båndoptager	type 7003	fabrikat Brüel & Kjær
Smalbåndsanalysator	type 2031	fabrikat Brüel & Kjær
Oktavbåndsanalysator	type 2134	fabrikat Brüel & Kjær
Vindmåler	type MKII	fabrikat Windmaster
Datalogger	type 3421A	fabrikat HP
Borddatamat	type 85	fabrikat HP

MÅLERESULTATER

Bilag 2 viser kontinuerlige udskrifter af de A-vægtede lydtrykniveauer i et målepunkt 20 m fra møllen i læsiden under forskellige driftsforhold.

Bilag 3 viser det totale energiækvivalente A-vægtede lydtrykniveau, målt over 2-minutters intervaller, i et målepunkt 20 m fra møllefoden i læsiden, som funktion af vindhastigheden i 10 meters højde. Bilaget repræsenterer en nettomåletid på ca. 7 timer.

Bilag 3A viser det gennemsnitlige, energiækvivalente, A-vægtede lydtrykniveau hidrørende fra møllens drift omregnet til en reference-afstand på 1 m fra møllenavet.

Bilag 3A viser endvidere et eksempel på beregningen af støjniveauet i en given afstand fra møllen under anvendelse af figuren øverst på bilaget.

Bilag 4-5 viser smalbåndsanalyser af støjen målt under forskellige driftsforhold.

Bilag 6 viser 1/3-oktav analyser af støjen målt under samme forhold som med bilag 4 og 5.

Det A-vægtede lydtrykniveau målt 20 m fra møllen i vingeplanet er fundet at være 1-3 dB lavere end niveauet målt 20 m fra møllen i læsiden.

Den fra møllen emitterede støj indeholder - subjektivt vurderet - ikke rentonekomponenter.

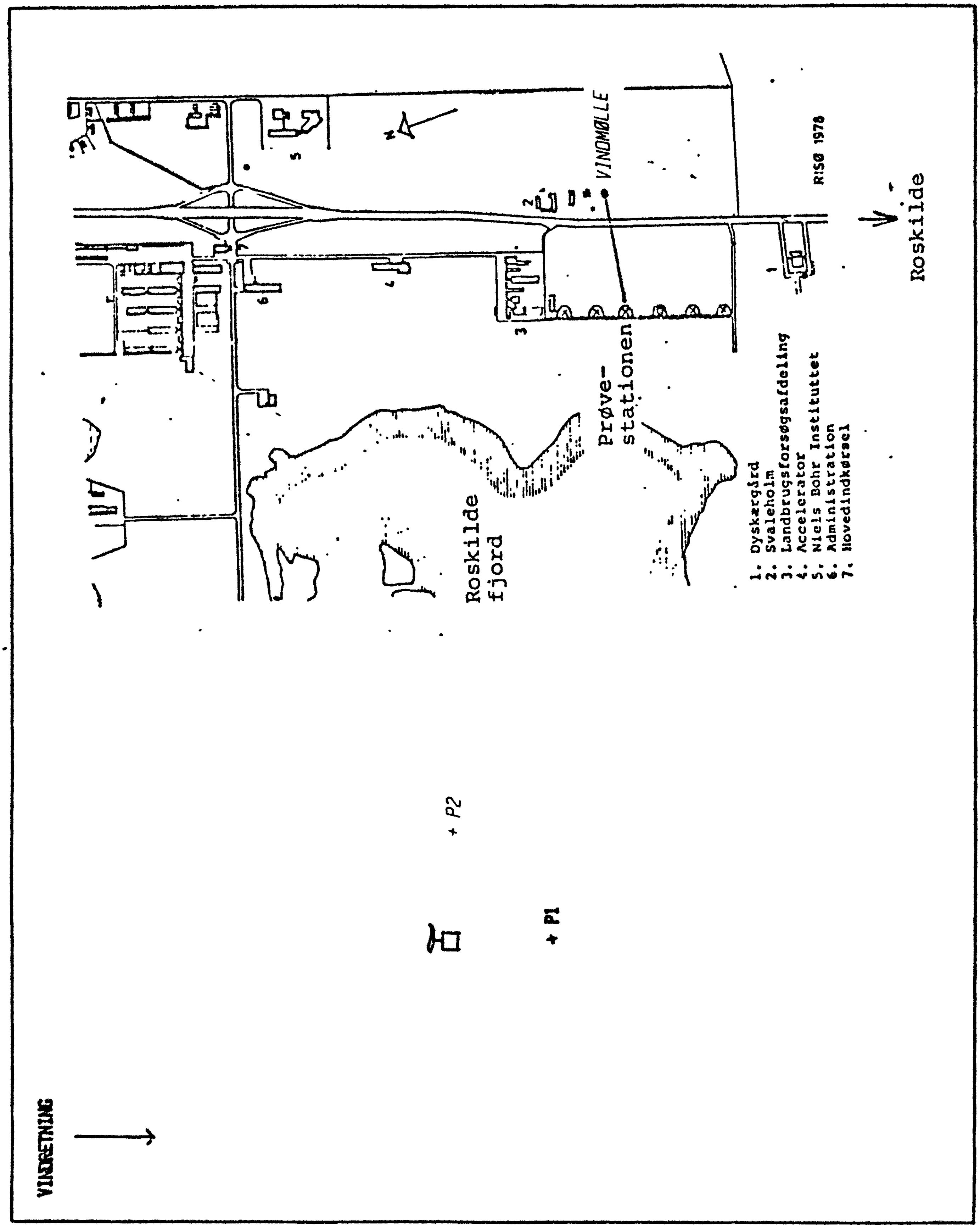
Støjemissionen fra møllen var subjektivt vurderet ikke domineret af maskinstøj, men af vingestøjen.

Der er i enkelte perioder observeret en støj af "hvinende" karakter fra vingerne, især ved vindhastigheder, hvor møllen skifter mellem de to generatorer.

DANSK KEDELFORENING
November 1984

Jørgen B. Kristensen / Poul Behnk
Støjteknisk afdeling

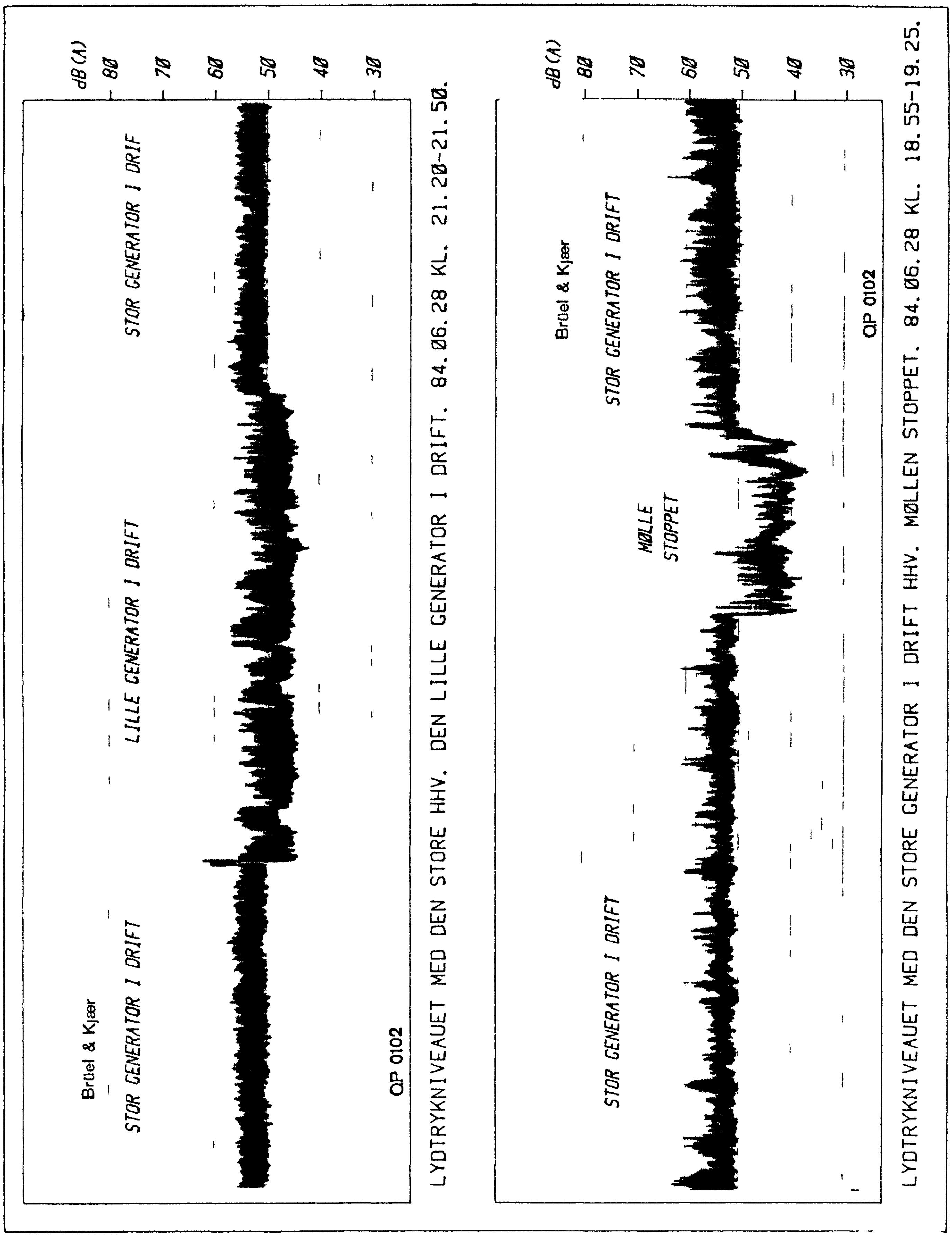
DANSK KEDELFORENING
ENERGI&MILJØ



SITUATIONSPLAN OG SKITSE OVER MAALEPUNKTER

WINDMATIC 55 kW VINDMØLLE. RISØ. SITUATIONSPLAN.	BILAG 1

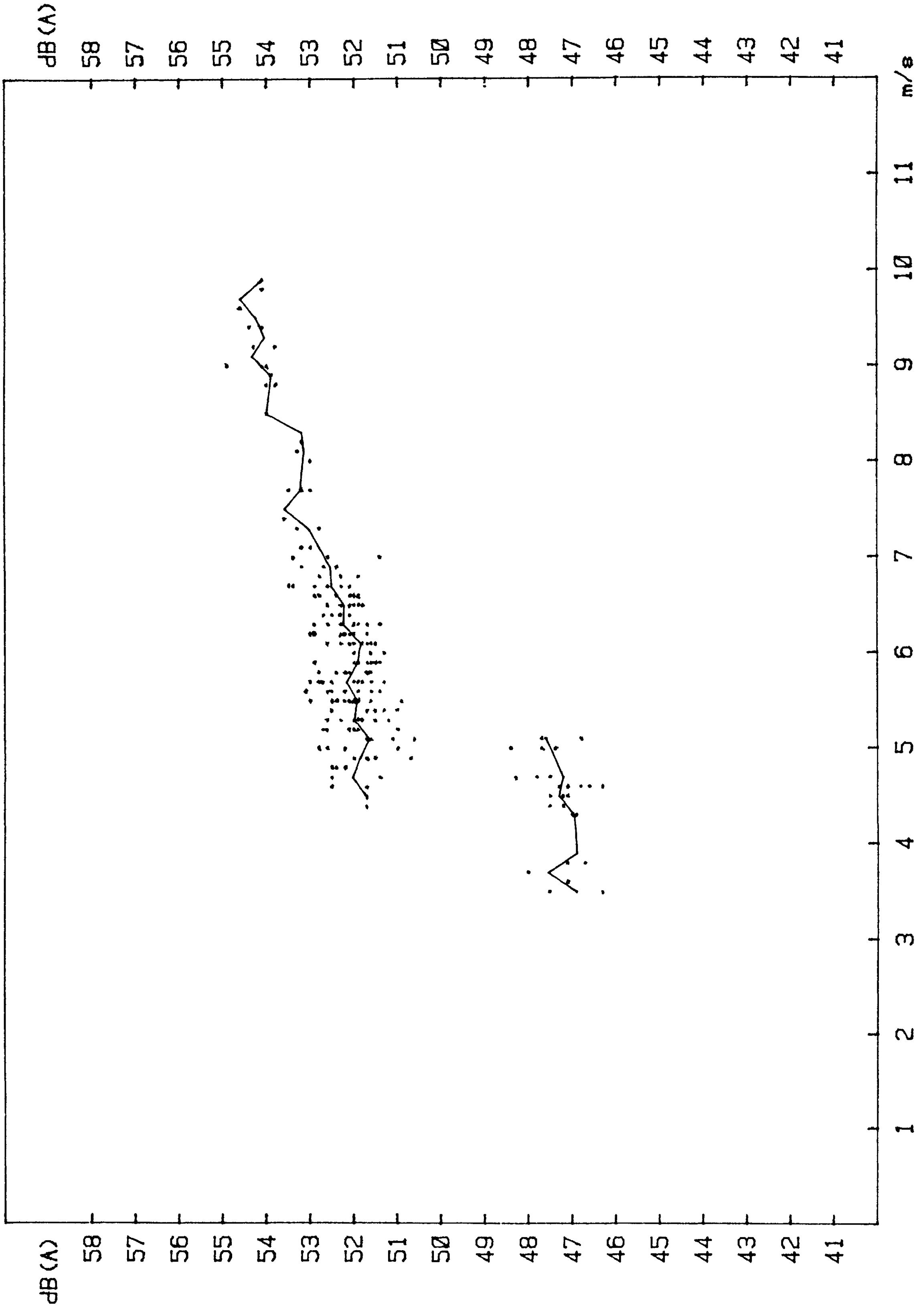
DANSK KEDELFORENING
ENERGI&MILJØ



DET A-VÆGTEDE LYDTRYKNIVEAU MAALT 20 METER FRA MØLLEN I LÆSIDEN.

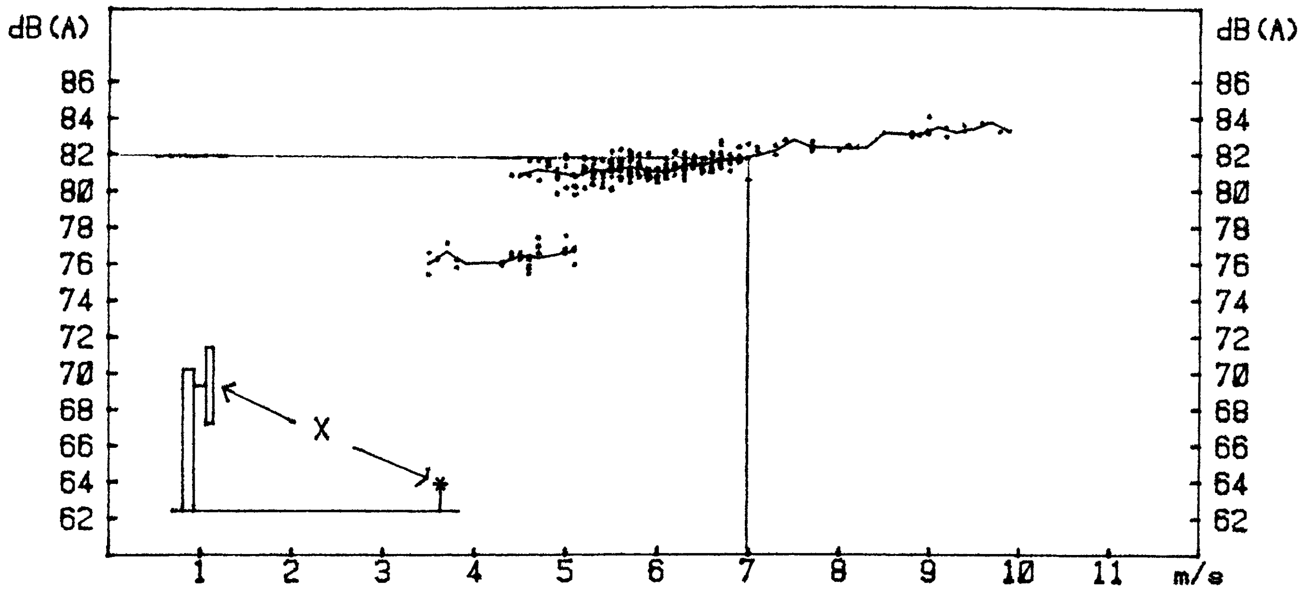
WINDMATIC 55 kW VINDMØLLE. RISØ. NIVEAUUDSKRIFTER.	BILAG 2

DANSK KEDELFORENING
ENERGI&MILJØ



DET ENERGIÆKVIVALENTE, A-VÆGTEDE LYDTRYKNIVEAU FOR 2-MINUTTERS INTERVALLER I MAALEPUNKT P1, 20 METER FRA MØLLEN I LÆSIDEN, SOM FUNKTION AF VINDHASTIGHEDEN I 10 METERS HØJDE.

WINDMATIC 55 kW PAA RISØ. MAALERESULTATER.	*BILAG 3*



DET GENNEMSNITLIGE, ENERGIÆKVIVALENTE, A-VÆGTEDE LYDTRYKNIVEAU I EN REFERENCEAFSTAND AF EN METER FRA MØLLENAVET, SOM FUNKTION AF VINDHASTIGHEDEN.

Det A-vægtede lydtrykniveau L_p i afstanden X meter fra møllenavet i læsiden bestemmes af udtrykket

$$L_p\ (X) = L_p\ (1) = \div\ 20 \times \log_{10}(X)$$

hvor L_p (1) er lydtrykniveauet aflæst af ovenstående kurve.

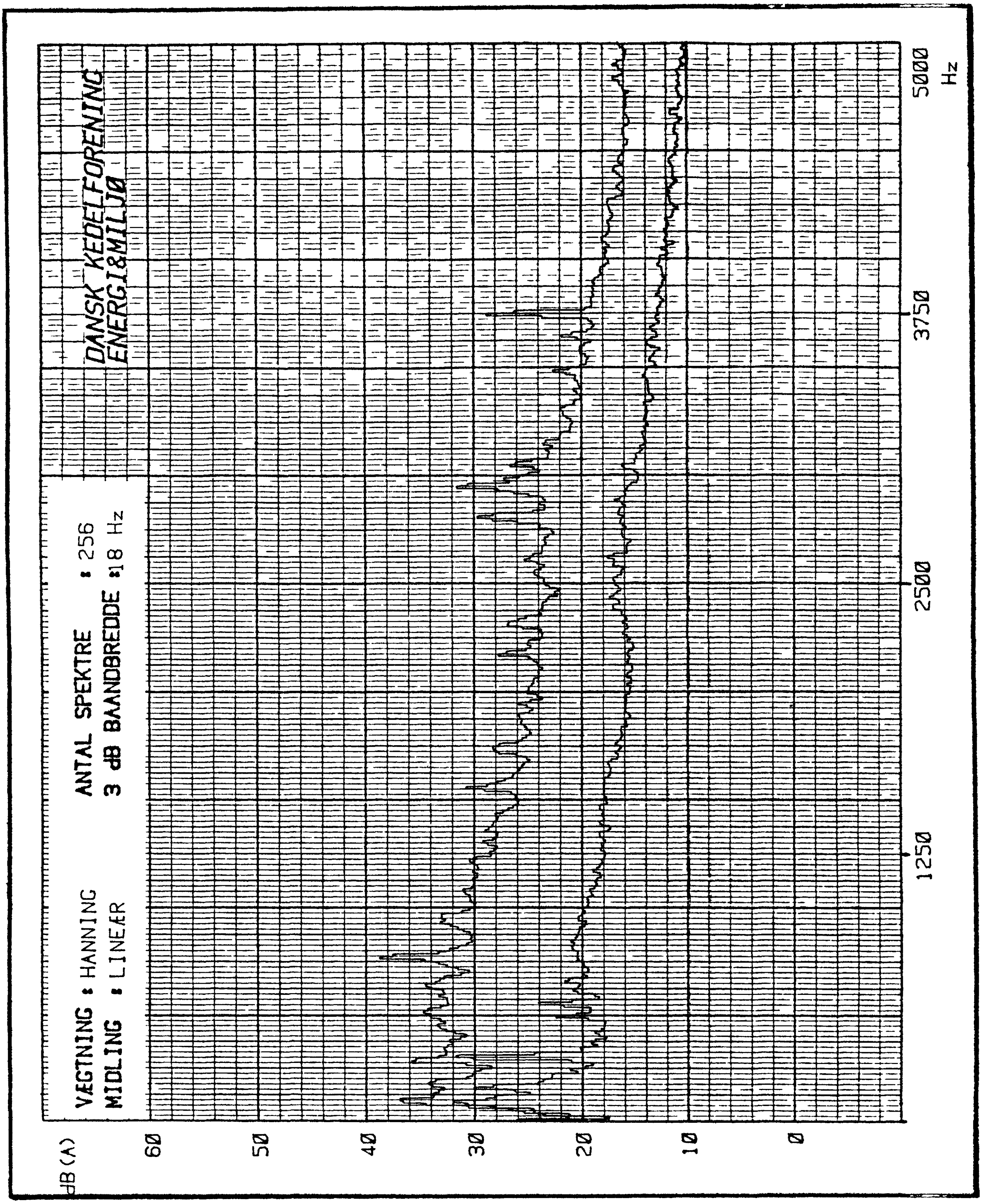
Dette udtryk må ikke anvendes i afstande mindre end 20 meter fra møllenavet.

<u>Eksempel</u>: Lydtrykniveauet i en afstand af 200 meter fra møllenavet ønskes bestemt ved en vindhastighed på 7 m/s.

1) Lydtrykniveauet ved 7 m/s aflæses af ovenstående kurve til 82 dB(A).

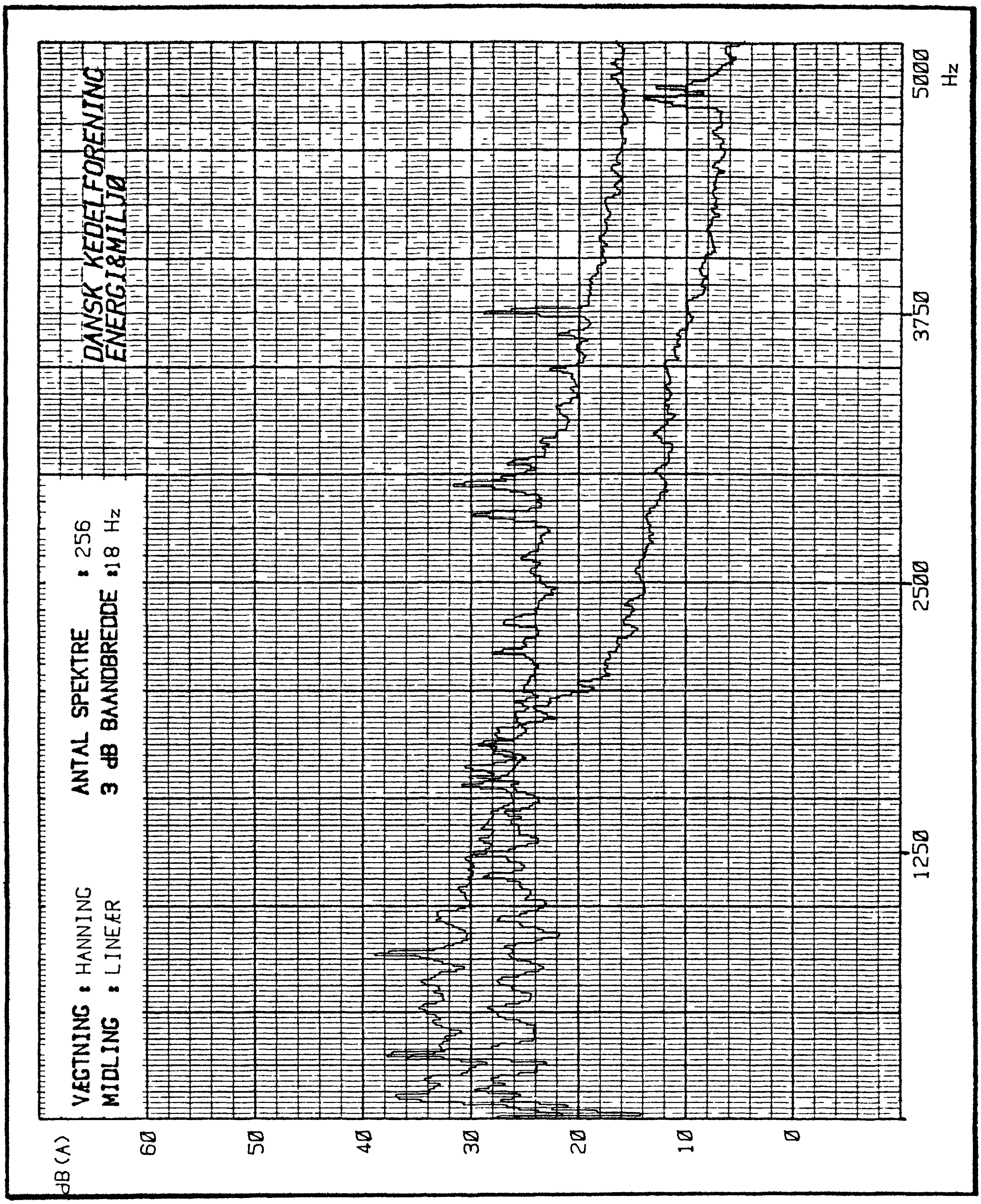
2) Ved anvendelse af formlen fås

$$L_p\ (200) = 82\ \text{dB(A)} - 20 \times \log_{10}(200)$$
$$= 82\ \text{dB(A)} - 46\ \text{dB(A)} = \underline{\underline{36\ \text{dB(A)}}}$$



SMALBAANDSANALYSE AF DET A-VÆGTEDE LYDTRYKNIVEAU.
MAALETIDSPUNKT : 84.06.28 KL. CA. 19.10.
MAALEPUNKT : 20 METER FRA MØLLEFODEN I LÆSIDEN.
ØVERSTE KURVE : MØLLE I DRIFT, STOR GENERATOR. LAeq= 53 dB(A).
NEDERSTE KURVE : MØLLE UDE AF DRIFT. LAeq= 43 dB(A).
VINDHASTIGHED I 10 METERS HØJDE : CA. 7 m/s.

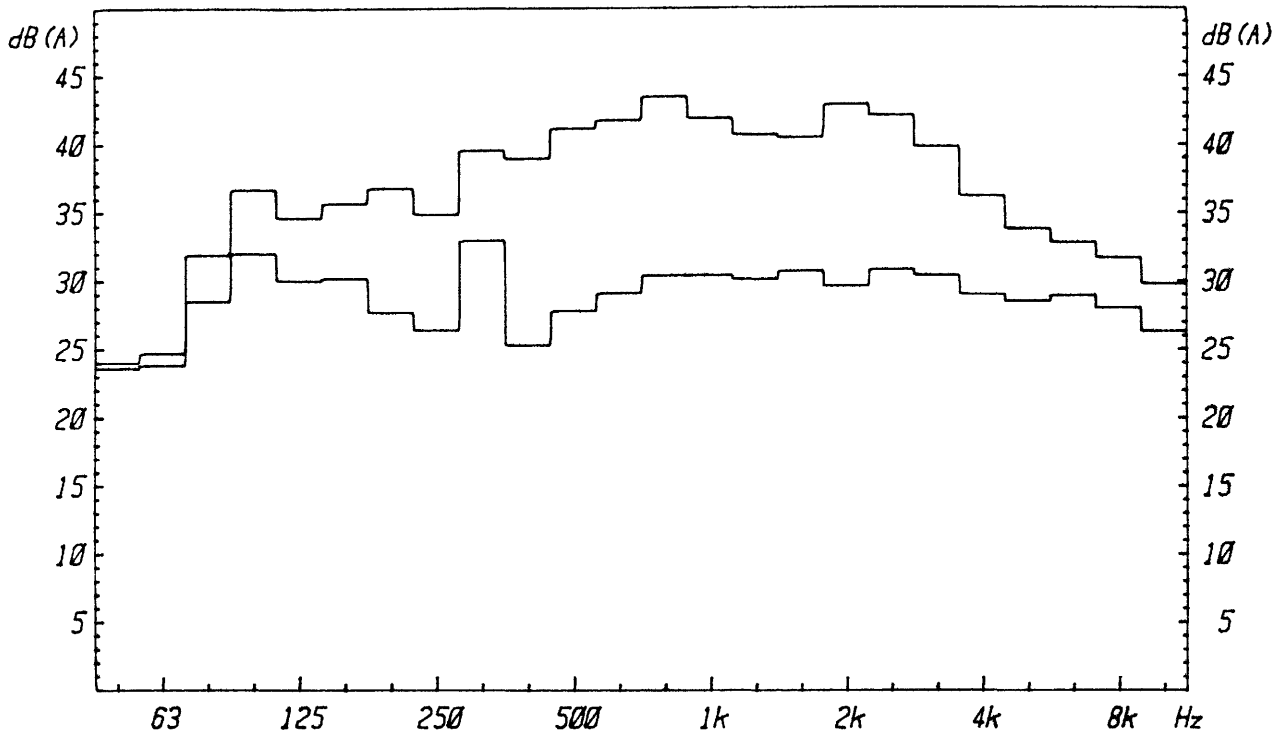
WINDMATIC 55 kW VINDMØLLE. RISØ. FREKVENSANALYSE	BILAG 4



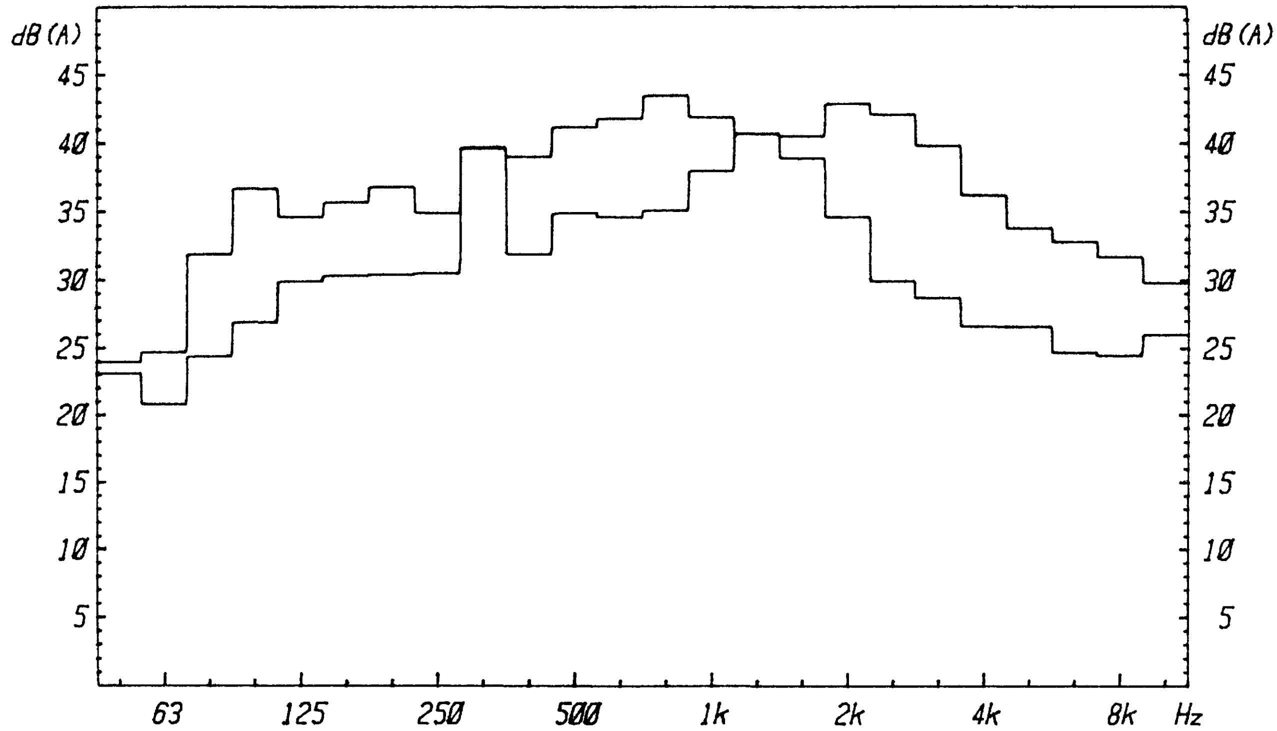
SMALBAANDSANALYSE AF DET A-VÆGTEDE LYDTRYKNIVEAU.
MAALETIDSPUNKT : 84.06.28 KL. CA. 22.50.
MAALEPUNKT : 20 METER FRA MØLLEFODEN I LÆSIDEN.
ØVERSTE KURVE : MØLLE I DRIFT, STOR GENERATOR. LAeq= 53 dB(A).
NEDERSTE KURVE : MØLLE I DRIFT, LILLE GENERATOR. LAeq= 48 dB(A).
VINDHASTIGHED I 10 METERS HØJDE : CA. 7 m/s. (ØVERST) HHV. 5 m/s (NEDERST)

WINDMATIC 55 kW VINDMØLLE. RISØ. FREKVENSANALYSE	BILAG 5

DANSK KEDELFORENING
ENERGI&MILJØ



ØVERST: MØLLEN I DRIFT PAA STOR GENERATOR. NEDERST: MØLLEN UDE AF DRIFT
VINDHASTIGHED I 10 METERS HØJDE : CA. 7 m/s



ØVERST: MØLLEN I DRIFT PAA STOR GENERATOR. VINDHASTIGHED CA. 7 m/s.
NEDERST: MØLLEN I DRIFT PAA LILLE GENERATOR. VINDHASTIGHED CA. 5 m/s.

1/3-OKTAV ANALYSER AF DET A-VÆGTEDE LYDTRYKNIVEAU MAALT 20 METER FRA MØLLEN I LÆSIDEN, UNDER FORSKELLIGE DRIFTSFORHOLD.

WINDMATIC 55 kW VINDMØLLE. RISØ. 1/3-OKTAV ANALYSER	BILAG 6

Risø National Laboratory **Risø – M – 2481**

Title and author(s)

Wind Turbine Test
Wind Matic WM15S

Troels Friis Pedersen

Date July 1986

Department or group

The Test Station for Windmills

Groups own registration number(s)

Project/contract no.

Pages 71 **Tables** 11 **Illustrations** 30 **References** 5

ISBN 87-550-1263-9

Abstract (Max. 2000 char.)

The report describes standard measurements performed on a Wind-Matic WM 15S, 55 kW wind turbine. The measurements carried out and reported here comprises the power output, system efficiency, energy production, transmission efficiency, rotor power, rotor efficiency, air-brakes efficiency, dynamical behaviour of the turbine, loads at cut-in and braking, rotor torque at stopped condition, and noise emission.

Descriptors

BRAKES; DYNAMIC LOADS; EFFICIENCY; HORIZONTAL AXIS TURBINES; MECHANICAL VIBRATIONS; NOISE; PERFORMANCE TESTING; POWER GENERATION; ROTORS

Available on request from Risø Library, Risø National Laboratory, (Risø Bibliotek, Forsøgsanlæg Risø), P.O. Box 49, DK-4000 Roskilde, Denmark.
Telephone (02) 37 12 12, ext. 2262. Telex: 43116, Telefax: (02) 36 06 09

Available on request from.
Risø Library,
Risø National Laboratory, P.O. Box 49,
DK-4000 Roskilde, Denmark
Phone (02) 37 12 12 ext.2262

ISBN 87-550-1263-9
ISSN 0418-6435